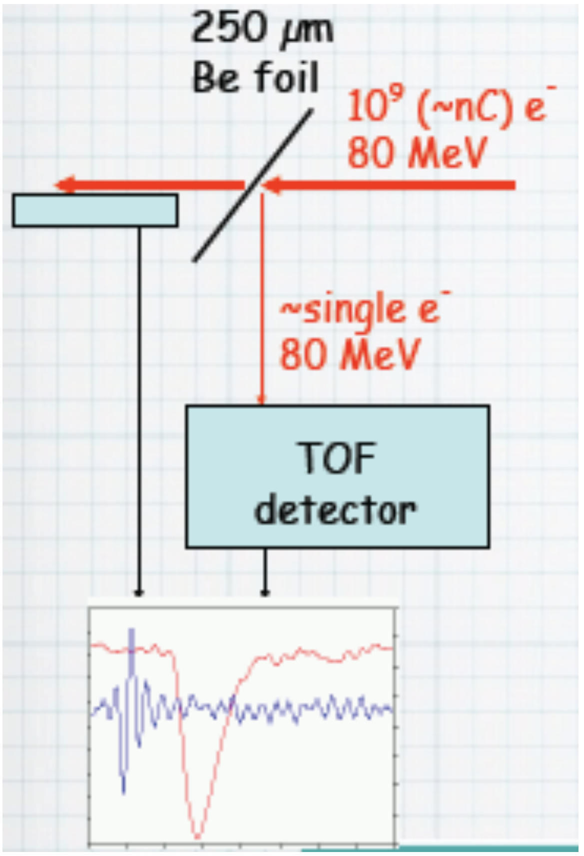
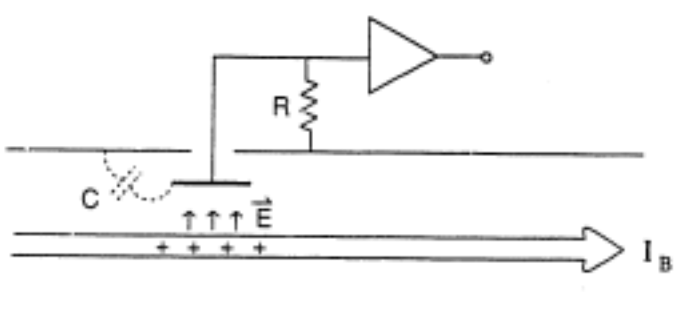
The single electron project

S.White, BNL

Nov. 29, Crakow timing workshop



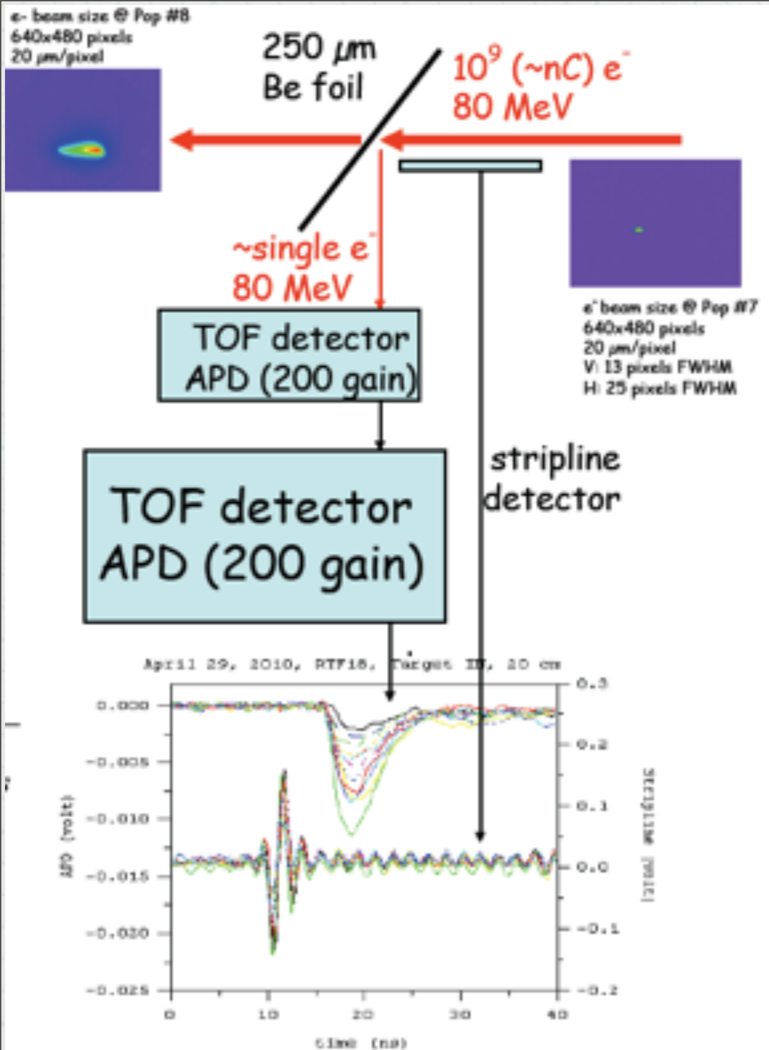


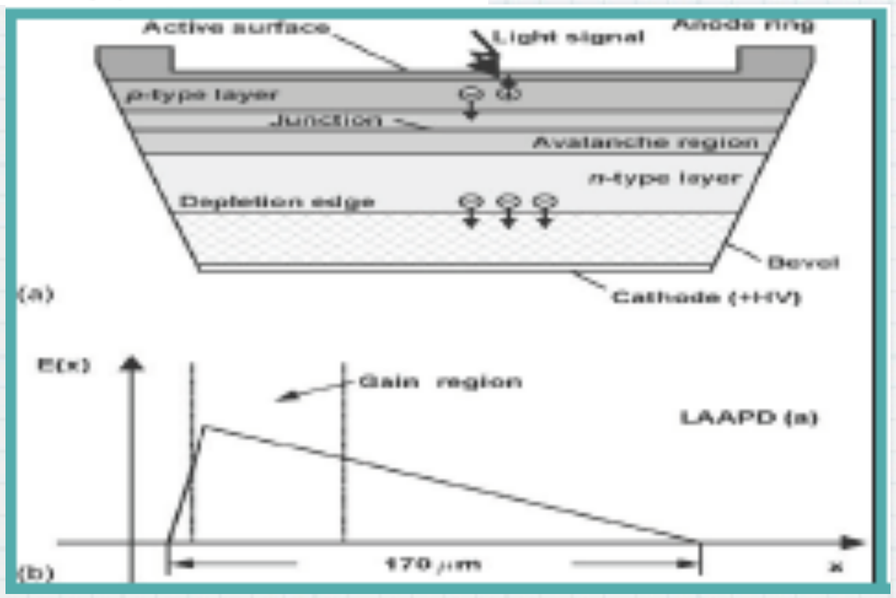
- a unique feature of ATF beam is 3 picosec bunch length(streak camera)
- could this be exploited to evaluate fast timing detectors?
- common technique for secondary beam design is successive dispersion and collimation
- this requires real estate

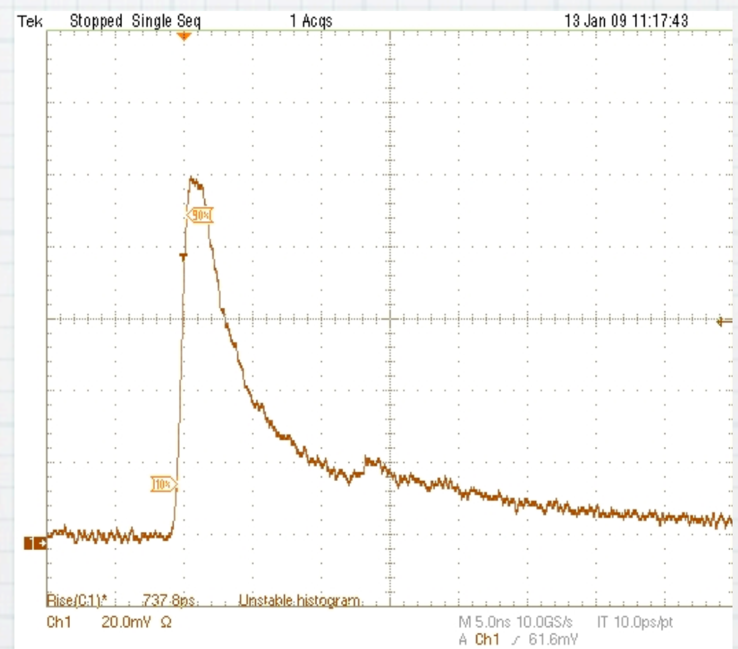
representing work of:
V. Yakimenko,
M.Fedurin, T. Tsang, M.Chiu, M.Diwan, G.Atoian(BNL)
K.McDonald(Princeton)

correspondents:
H.Frisch, J. Va'vra, K.Goulianos, D.Acker, I.Mousienko,
P. Vaska, M.Suyama, C. Royon

Why is a 100 MeV, single electron, 3 picosecond beam interesting?







Deep diffused avalanche photodiode

650 picosecond risetime (β's)

"A 10 picosecond time of flight detector using APD's", SNW et al.

100 years of subatomic Structure

- Rutherford, Geiger, Marsden (1909)
  - –Atom's 100th Birthday!
  - –Rutherford's teacher, JJ Thomson, discovered electron 10 years earlier
- "counter experiment"
  - –Beam of 5 MegaVolt α particles from Radium C decay
- naive idea to use Rutherford scattering for a "1 step" secondary beam

JJ Thomson & Ernest Rutherford

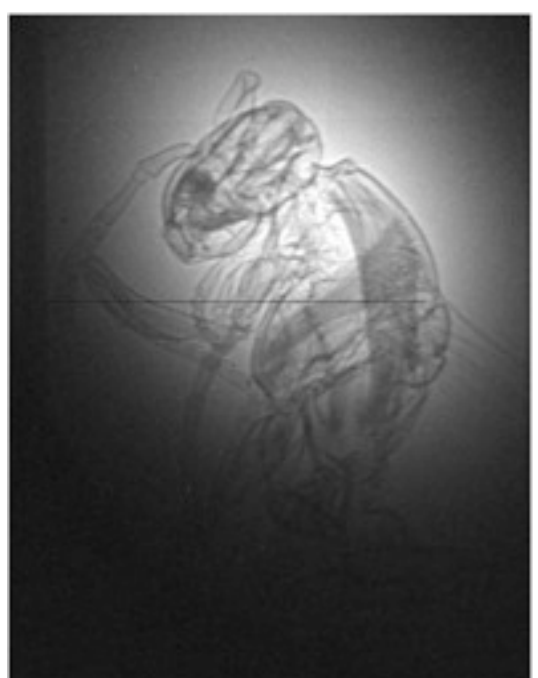
- **Question: with an incident beam of 10^9 60-80 MeV electrons, a ~1 mm target (Al or Be), how many are scattered @90 degrees into a ~1cm^2 detector 30 cm away?**

  Answer: ~1 !

- calculations presented in:"LBNE energy calibration using a 100 MeV electron accelerator"-SNW& Vitaly Yakimenko http://arxiv.org/abs/1004.3068
- small accelerators previously used for calibration. ie:
- **Super K made good use of a 5-16 MeV medical accelerator -Mitsubishi ML-15MIII. They used a conventional secondary beam design (requires space)**

Background issues

- It would be almost impossible to calculate, from first principles, detector backgrounds from scraping, etc to the level of ~1cts/pulse
- Our approach has been to focus entirely on APD based devices where rates and energy deposit dependent primarily on area and effective depth
- Vitaly's intuition that such backgrounds low at ATF
- the bee:



Wide angle electron scattering

Approximations to Hofstadter' s form:

$$\text{Rutherford}[\theta\_, Z\_, \text{EeMeV}\_] := 1/4\,(Z * \alpha_{EM})^2 \frac{\hbar c1^2}{\text{EeMeV}^2} \text{Csc}[\theta/2]^4$$

$$\text{Mott}[\theta\_, Z\_, \text{EeMeV}\_] := \text{Rutherford}[\theta, Z, \text{EeMeV}] * \text{Cos}[\theta/2]^2 \left(1 + \frac{\pi * Z * \alpha_{EM} * \text{Sin}[\theta/2] * (1 - \text{Sin}[\theta/2])}{\text{Cos}[\theta/2]^2}\right)$$

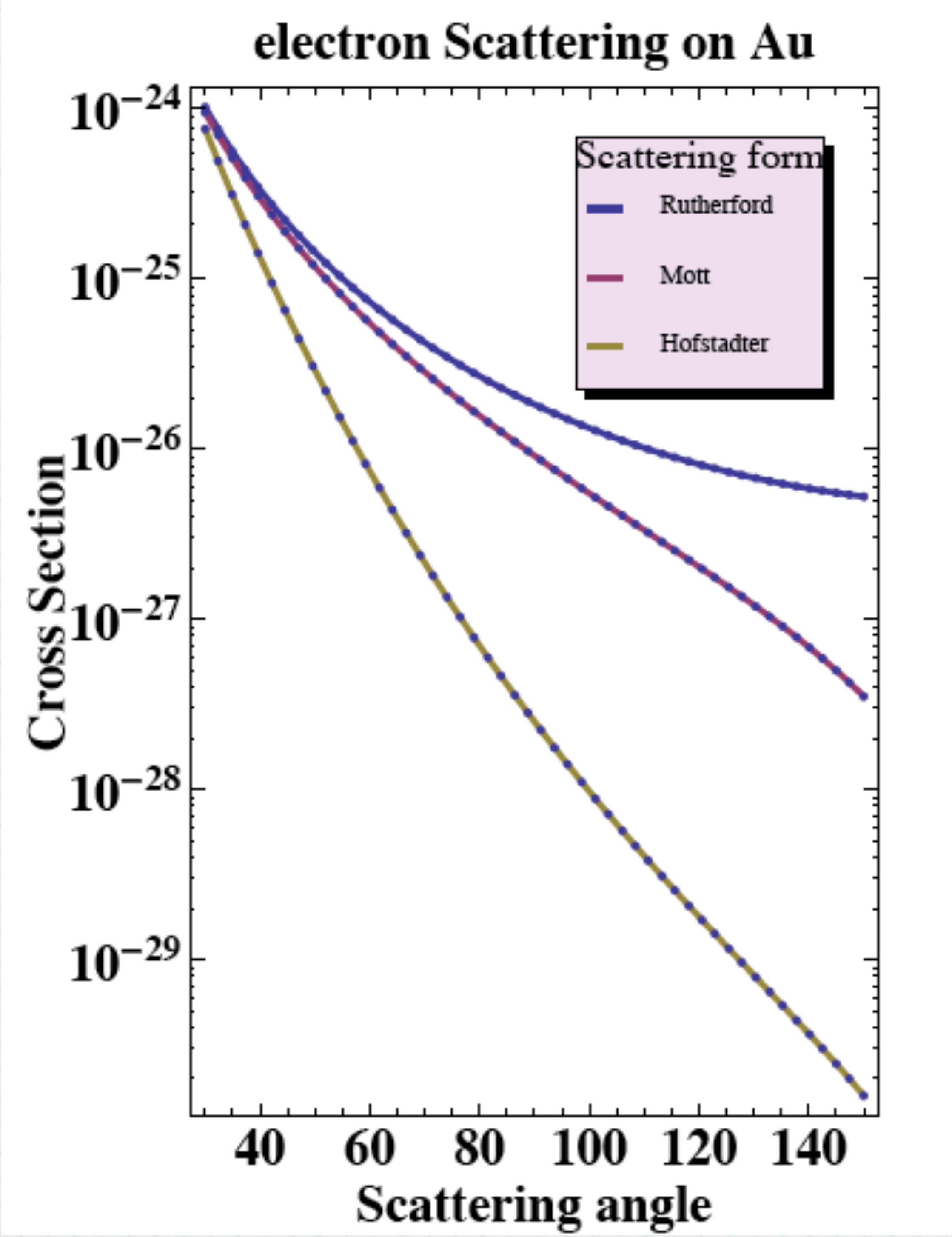
$$Q[\theta\_, \text{EeMeV}\_] := \frac{2 * \text{EeMeV}}{\hbar c} \text{Sin}[\theta/2]$$

$$\rho[r\_, a\_] := \frac{1}{8\pi\,(a)^3} \text{Exp}[-r/a]$$

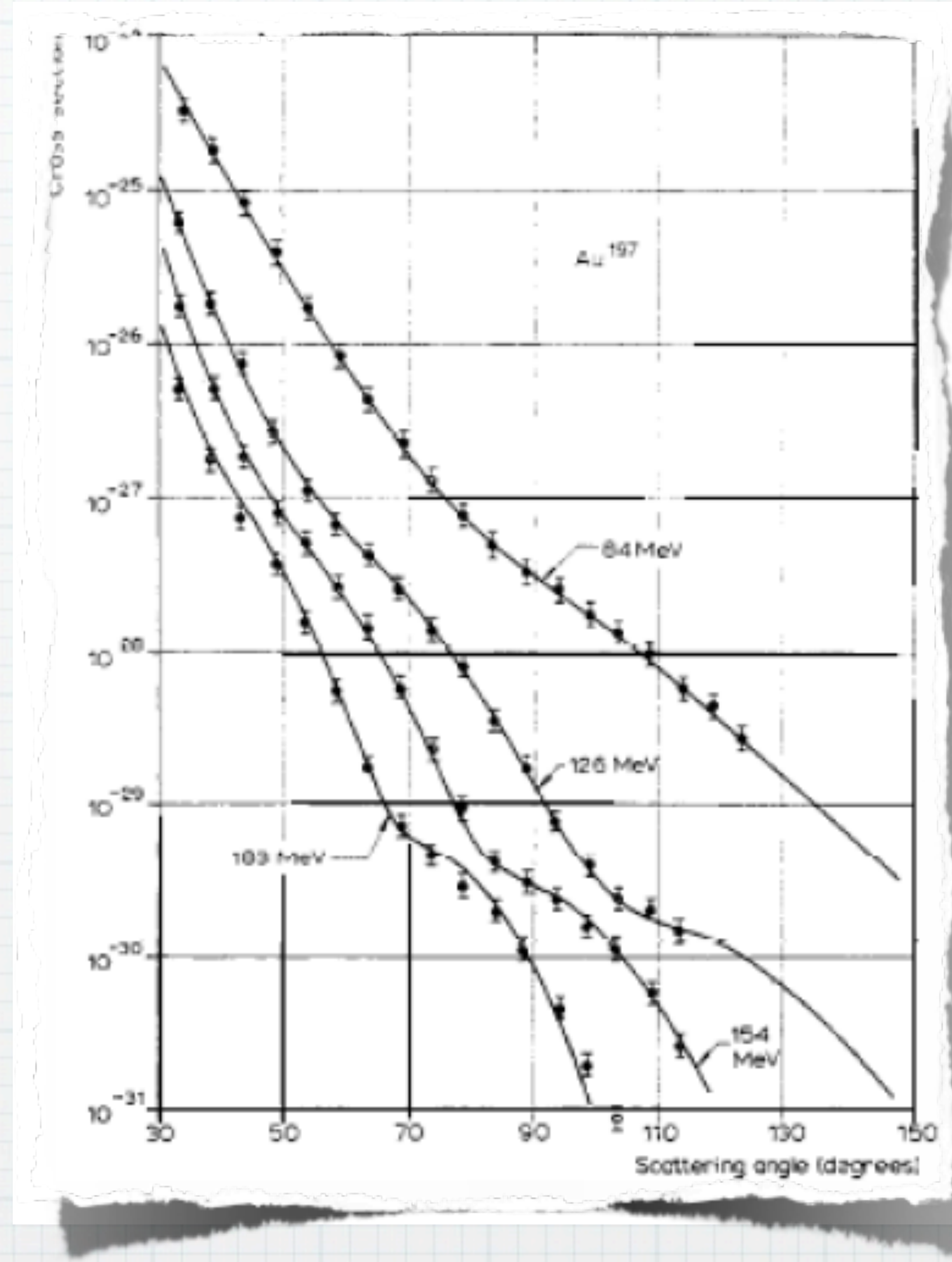
$$\text{FormFactor}(\theta\_, a\_, \text{EeMeV}\_) := \frac{4\pi \int_0^\infty r\,\rho(r, a) \sin(r\,Q(\theta, \text{EeMeV}))\,dr}{Q(\theta, \text{EeMeV})}$$

$$\text{Hofstadter}[\theta\_, Z\_, \text{EeMeV}\_, a\_] := \text{Mott}[\theta, Z, \text{EeMeV}] * \text{FormFactor}[\theta, a, \text{EeMeV}]^2$$

this calculation

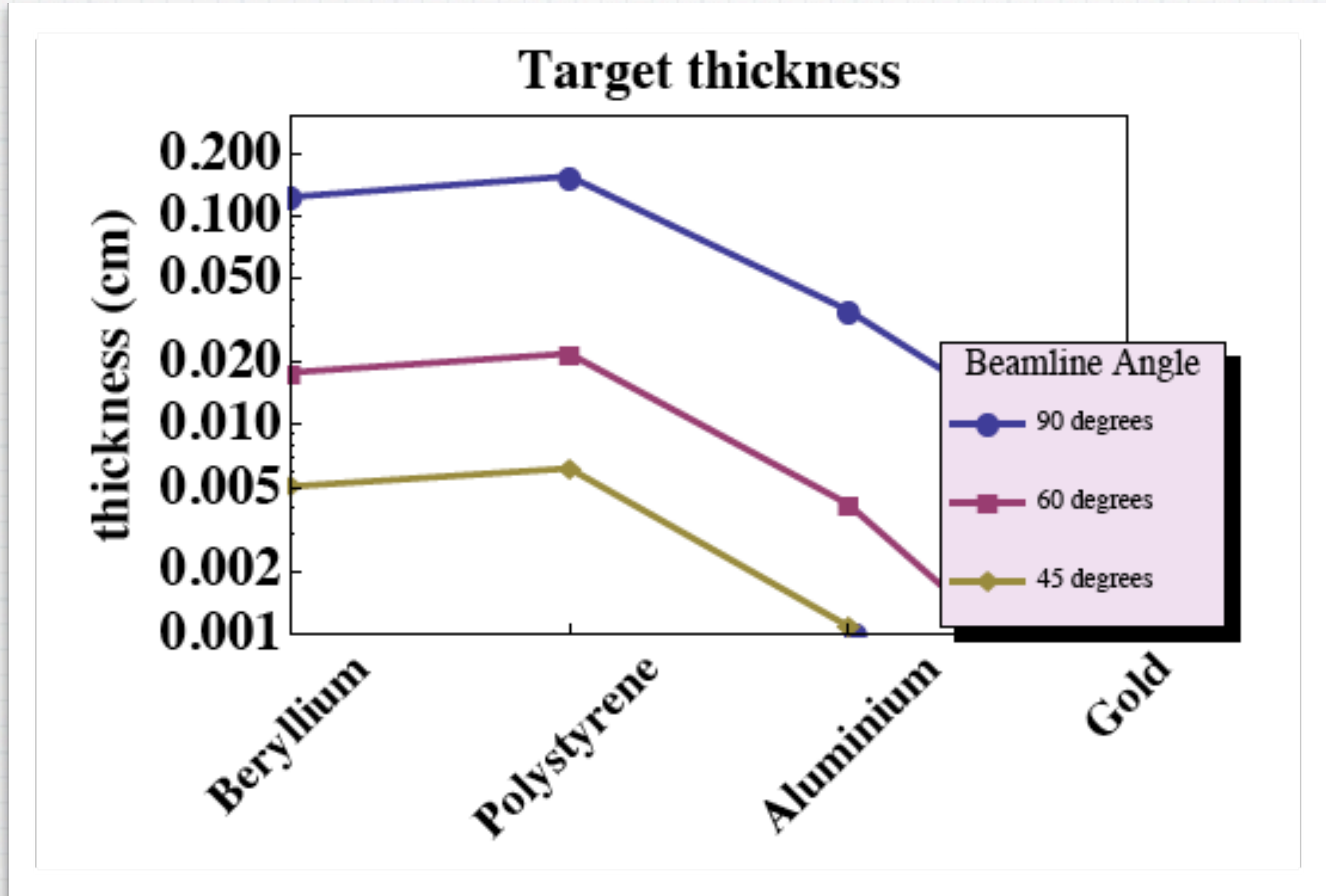


Hofstadter

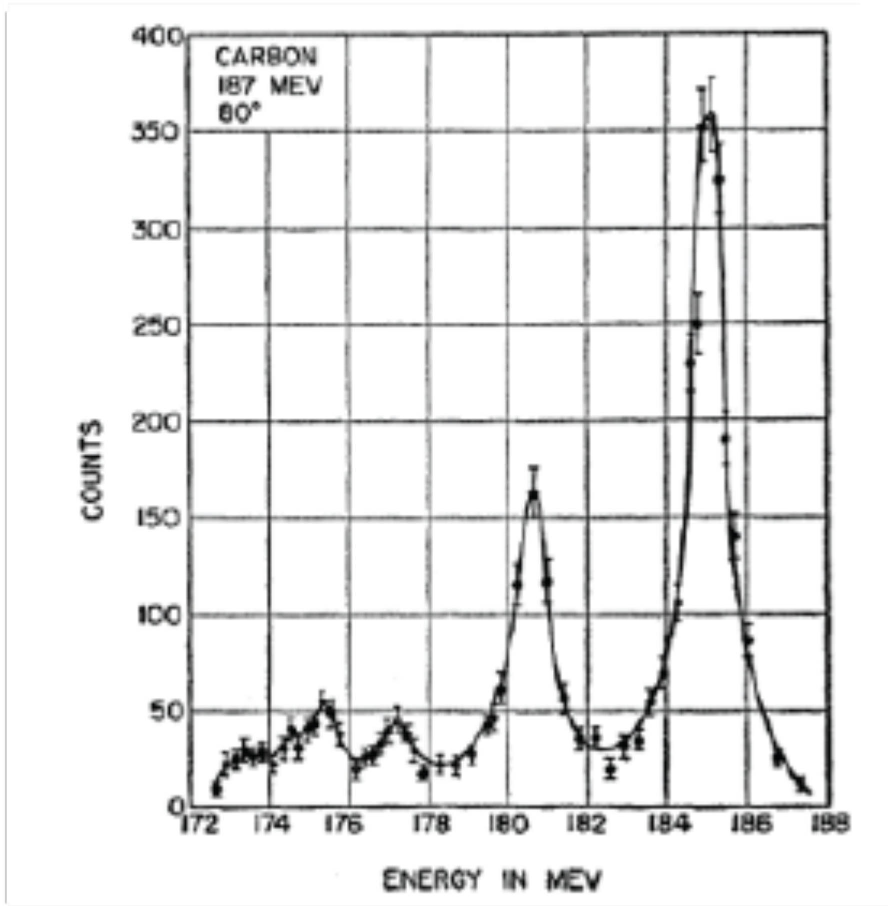


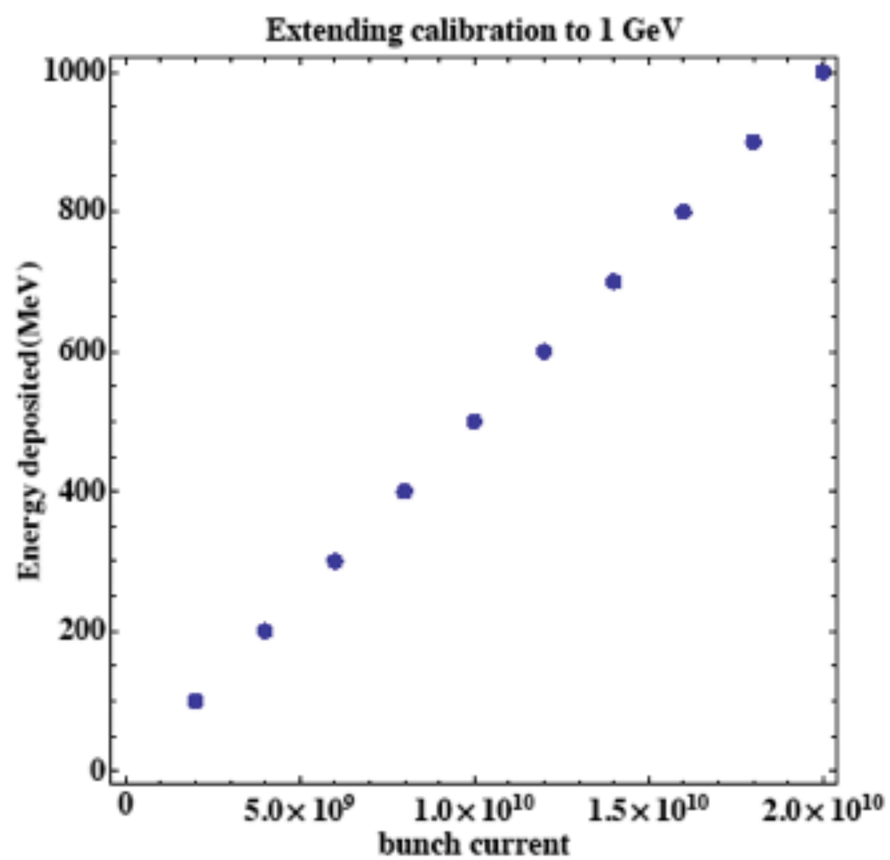
$$t90 = \text{Table}\left[.5 * \left(\frac{\text{Foils[[i, 3]]}}{M_p * \text{Foils[[i, 2]]}} * \text{Correction[[i]]} * \text{Flux} * d\Omega * \text{Hofstadter[90 * Degree, Foils[[i, 1]], 62, Foils[[i, 6]]]}\right)^{-1}, \{i, 4\}\right];$$

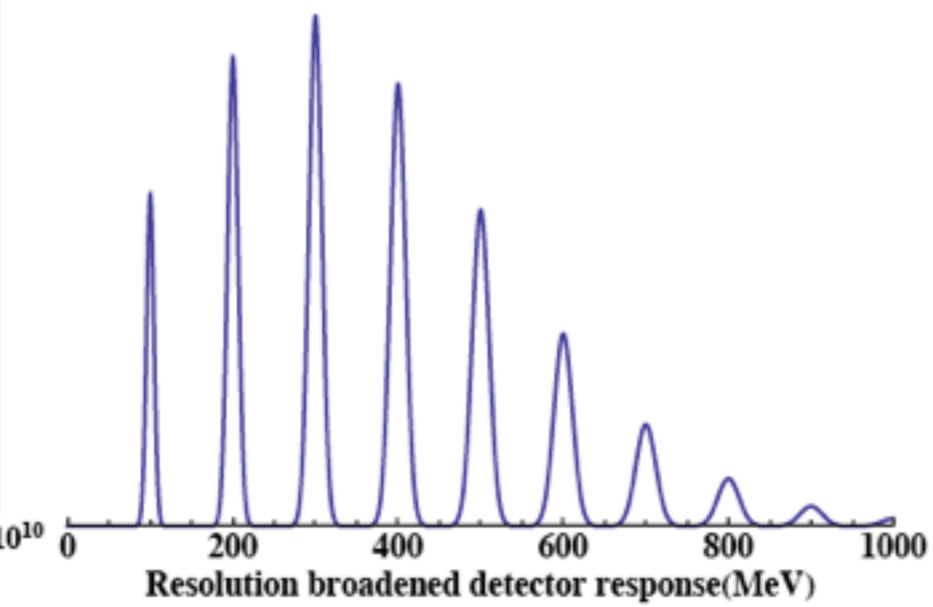
	Beryllium	Polystyrene	Aluminum	Gold
45^0	0.00507424	0.00619767	0.00108573	0.0000493743
60^0	0.0178675	0.0219929	0.00417395	0.000283
90^0	0.123976	0.15564	0.0354221	0.0050626



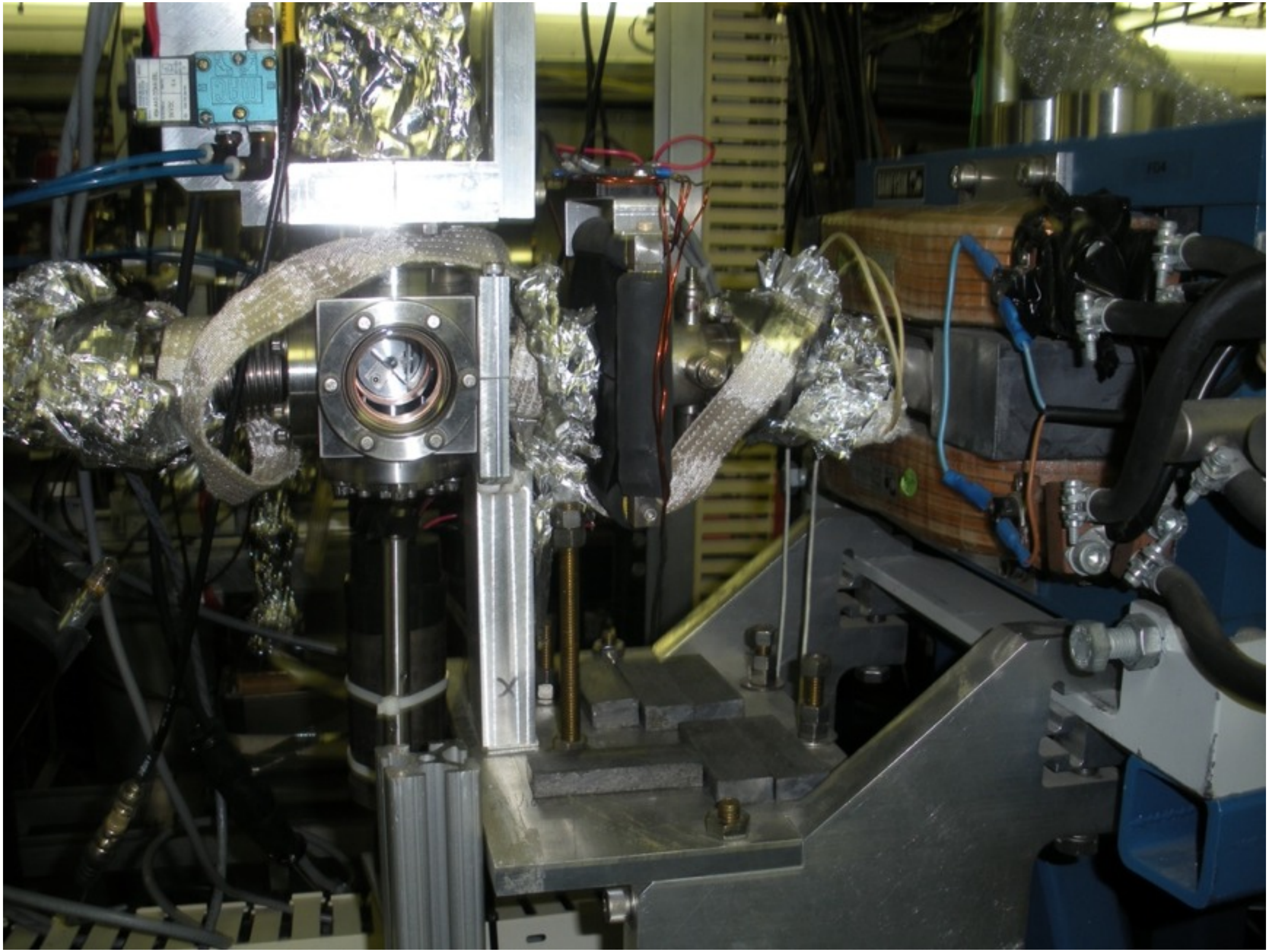
Interesting features for calibration





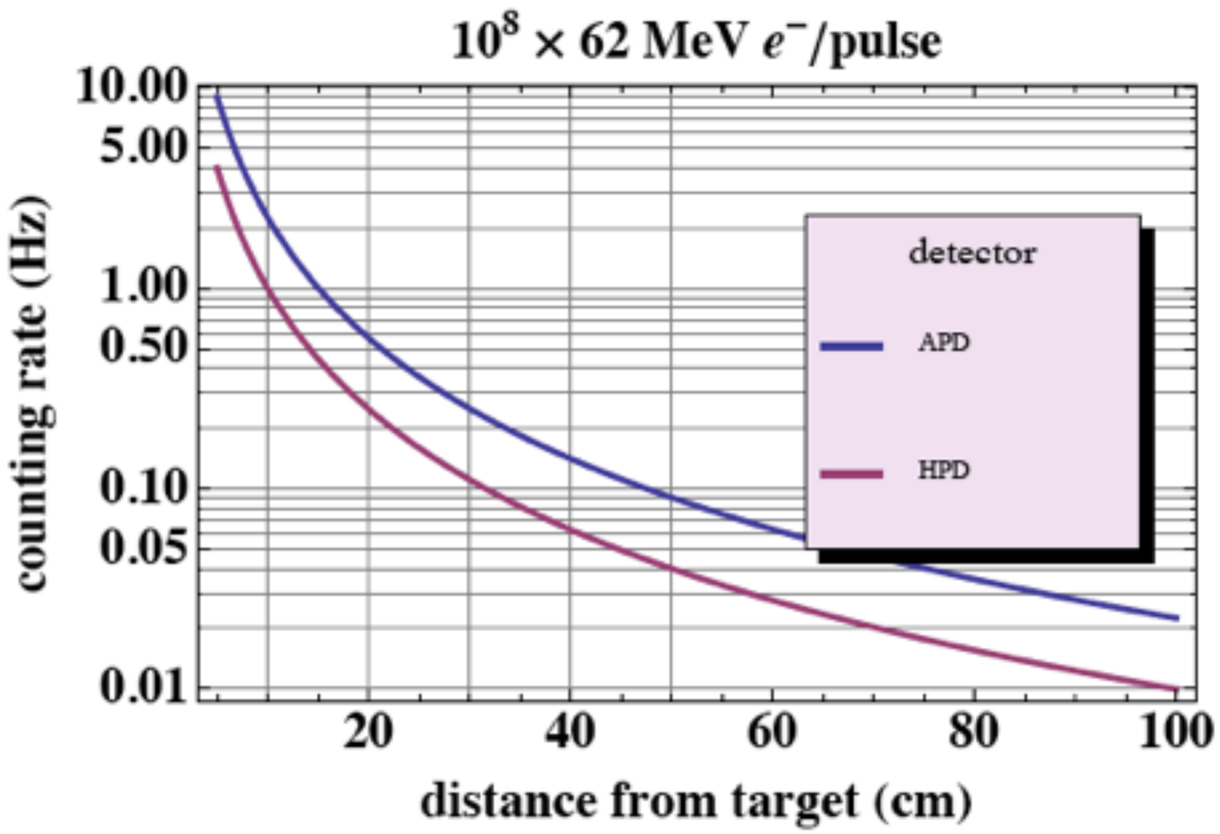


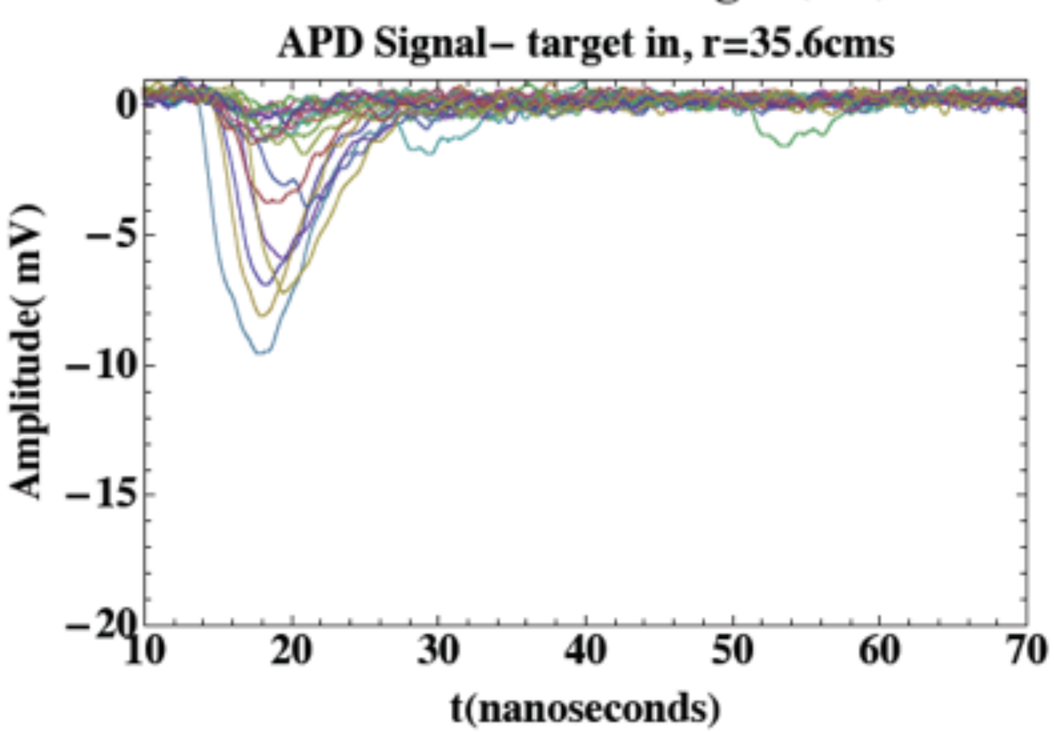
the beamline

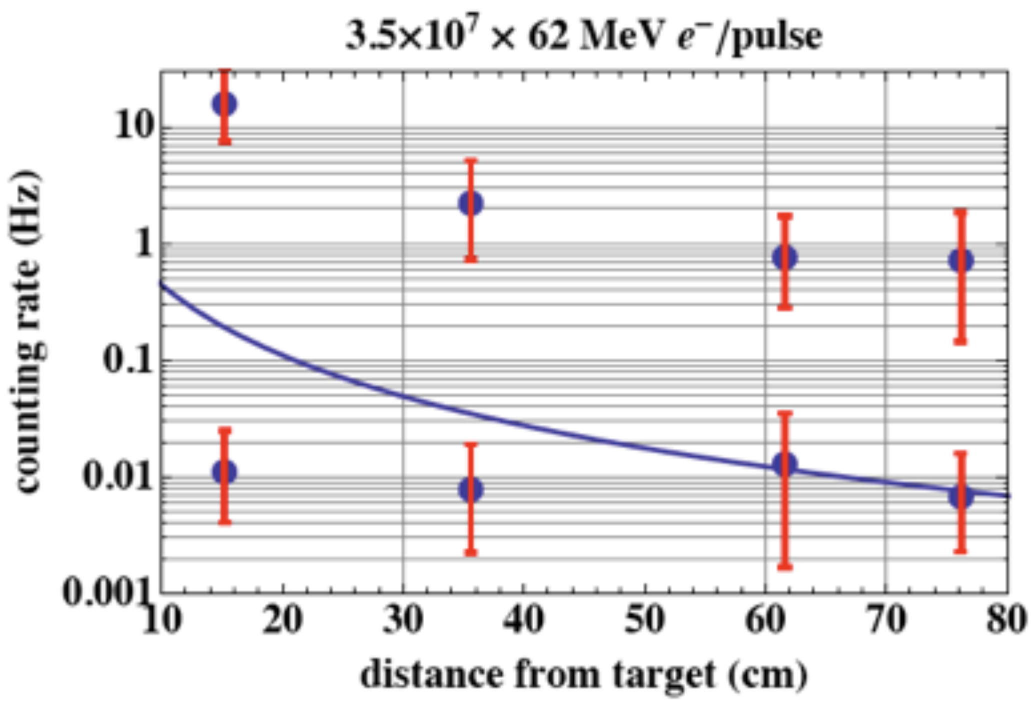


Initial tests (Al)

- “target out” background well below scattered rate
- “target in” rate ~10* calculation
- signal has v=c
- 1 X0 not effective
- concluded few MeV gamma

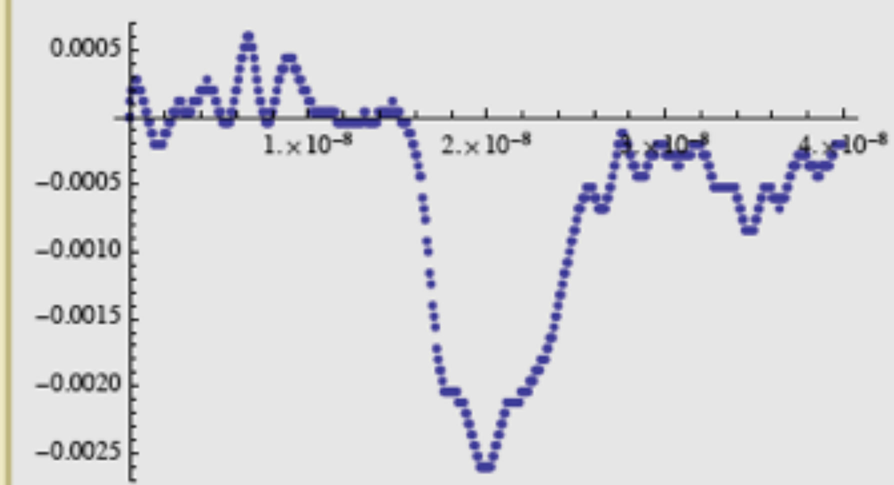






Al is very messy!

```
pl = ListPlot[Transpose[{time, dataA}], PlotRange → All]
```



Beryllium is excellent!

ENERGY LEVELS OF A = 21–44 NUCLEI (VII) 207

TABLE 27.4
Energy levels of ^{27}Al

E_x [keV]	$2J^\pi;2T$	τ_m	E_x [keV]	$2J^\pi;2T$	τ_m or Γ	E_x [keV]	$2J^\pi;2T$	τ_m or Γ
0	5^+	stable	7997 *1*	9		9600.7 9	3	12 *2* eV
843.76 *3*	1^+	50 *2* ps	8037 *1*	7	0.62 *5* fs	9599.2 *14*	3^-	2.5 *2* keV
1014.45 *3*	3^+	2.15 *10* ps	8043 *2*	(5^+-9^+)		9628.5 9	1^-	2.76 *14* keV
2211.1 *6*	7^+	38.4 *9* fs	8065 *2*	$(3,5)^+$	$\mathcal{J}\times 29$ *8* as	9634.5 9	5^+	18 *5* eV
2734.9 *7*	5^+	12.9 *18* fs	8097 *1*	5		9658 *2*		
2982.00 *5*	3^+	5.7 *3* fs	8130 *3*	1^+		9664.7 *8*	5^+	24 *8* eV
3004.2 *8*	9^+	85 *5* fs	8136 *1*	5		9664.8 *20*	1^-	5.82 *10* keV
3680.4 9	1^+	7.8 *17* fs	8182.1 *13*	3^-		9692 *3*		
3956.8 *4*	3^+	3.6 *3* fs	8287 *1*	9^-		9715.9 *8*	3^+	
4054.6 *5*	1^-	10.6 *18* fs	8324 *1*	5^+		9742 *3*		
4410.2 *4*	5^+	1.7 *2* fs	8361 *3*			9762.8 *8*	5^+	18 eV
4510.3 *5*	11^+	320 *20* fs	8376 *1*	$(3,5)^+$		9796.3 9	7^+	4 *3* eV
4580.0 *8*	7^+	7.7 *8* fs	8396 *1*	11		9821.6 9	3^+	18 eV
4811.6 *5*	5^+	2.2 *3* fs	8408 *3*			9834.4 *10*	1^-	3.0 keV
5155.6 *8*	3^-	3.3 *4* fs	8420.7 *10*	$(3,5)^+$		9839.7 *10*	5	1.0 *2* eV
5248.0 *6*	5^+	< 6 fs	8442 *1*	7	0.72 *14* fs	9846.6 *10*	1^+	210 eV
5419.9 *9*	9^+	< 20 fs	8490.3 *12*	5^+		9867 *3*		
5432.8 *10*	7	10 *3* fs	8521 *2*	$(1-7^+)$		9883 *3*		
5438.4 *8*	5^-	8 *6* fs	8537 *1*	5		9893 *2*		
5499.8 *8*	11^+	< 10 fs	8553.0 *3*	3		9921.9 9	3^-	1.8 keV
5550.9 *5*	5	3.8 *7* fs	8586 *1*	7		9930.4 9	1^-	1.35 keV
5667.3 *12*	9^+	16 *4* fs	8597.6 *3*	3^-	0.56 *4* eV	9941.3 9	7	
5751.6 *10*	1^+	< 15 fs	8675 *1*	$(7,9^+)$	$\mathcal{J}\times 18$ *5* as	9953.0 *16*		
5827.0 *8*	3^-	< 30 fs	8693 *2*	(9–13)		9955.5 *10*	3	
5960.3 *7*	7	2.4 *17* fs	8708.7 *3*	1^+	7.6 *6* eV	9960.3 9	5^-	8 eV
6080.8 *9*	3	4.8 *11* fs	8716.6 *6*			9962.8 9	5^+	12 eV
6115.8 *6*	5		8732.2 *5*	7^-	0.19 *3* eV	9976.8 9	$(5,7)^+$	11 *2* $\mathcal{J}^{-1}$ eV
6158.4 *7*	3^-	< 20 fs	8753.6 *6*	5	1.05 *13* eV	9990.8 9	7^-	10 eV
6284.7 *15*	7^+	7 *3* fs	8774.2 *6*	5^+	3.7 *3* eV	9999.9 *10*	5	
6462.8 *13*	5	1.12 *12* fs	8804 *1*			10008 *3*		
6477.3 *9*	7^-	2.6 *4* fs	8825 *3*			10024.3 9	5^+	35 eV
6512.2 *11*	9	14 *3* fs	8861 *3*			10075 *3*		

we now have a backlog of high quality data, with different timing detectors, absorbers and distance to target. Requires ~1 week analysis to make suitable for publication.

- In ATF proposal we request:3 days beam studies, 10 days detector R&D beam time

Our collaboration will provide:

- complete characterization of secondary beam (optimize “target out” background rates)
- currently data quality depend on resident ATF accelerator expertise in beam tuning-> codify procedure for beam setup
- “oscilloscope-based” data acquisition system initially slow and best understood scope was 500 MHz one
- ->make permanent installation based on ~$1000, 4-channel scope on a chip (DRS4 evaluated by us on loan from Frisch). Also higher performance chips in development (u.Chicago,Hawaii, Orsay,Saclay)- we will provide this.

- high daq rate and fast online feedback

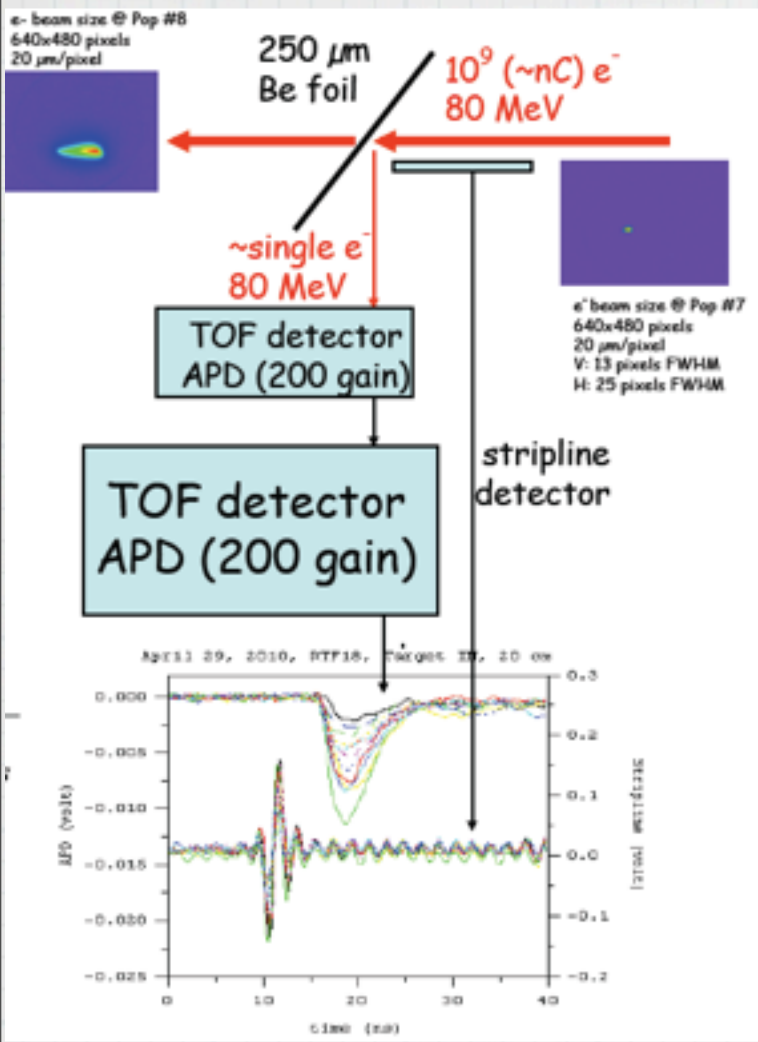
High Resolution, high rate TOF R&D

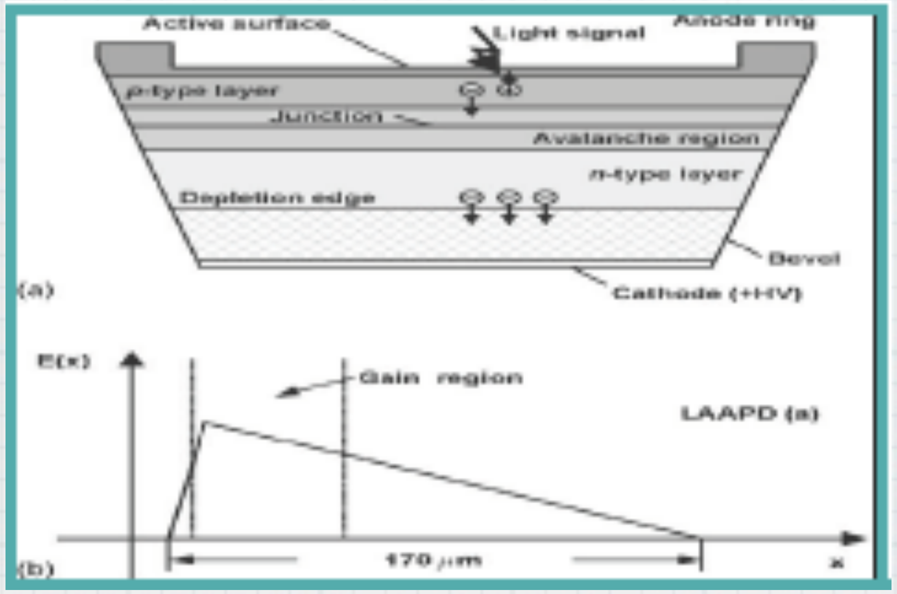
proposal to BNL Accelerator Test Facility

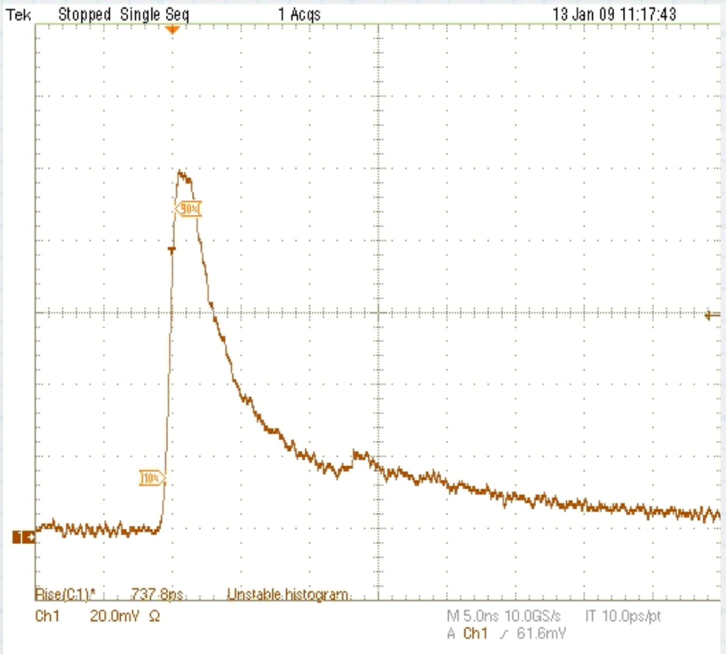
- Growing interest in Nuclear and High Energy Physics in timing detectors with ~10^{-11} sec time resolution. ie
- -extension of pid to new kinematic region in PHENIX(scale 100 psec@5m to distance of ~1/2 m)
- -pileup rejection at the LHC in forward physics(LHC bunch interaction rms=170 picosec)

- lifetime and rate limit of current technologies a major issue
- new progress in timing possible similar to Si tracking of last 20 years

Why is a 100 MeV, single electron, 3 picosecond beam interesting?







Deep diffused avalanche photodiode

650 picosecond risetime (β's)

"A 10 picosecond time of flight detector using APD's", SNW et al.

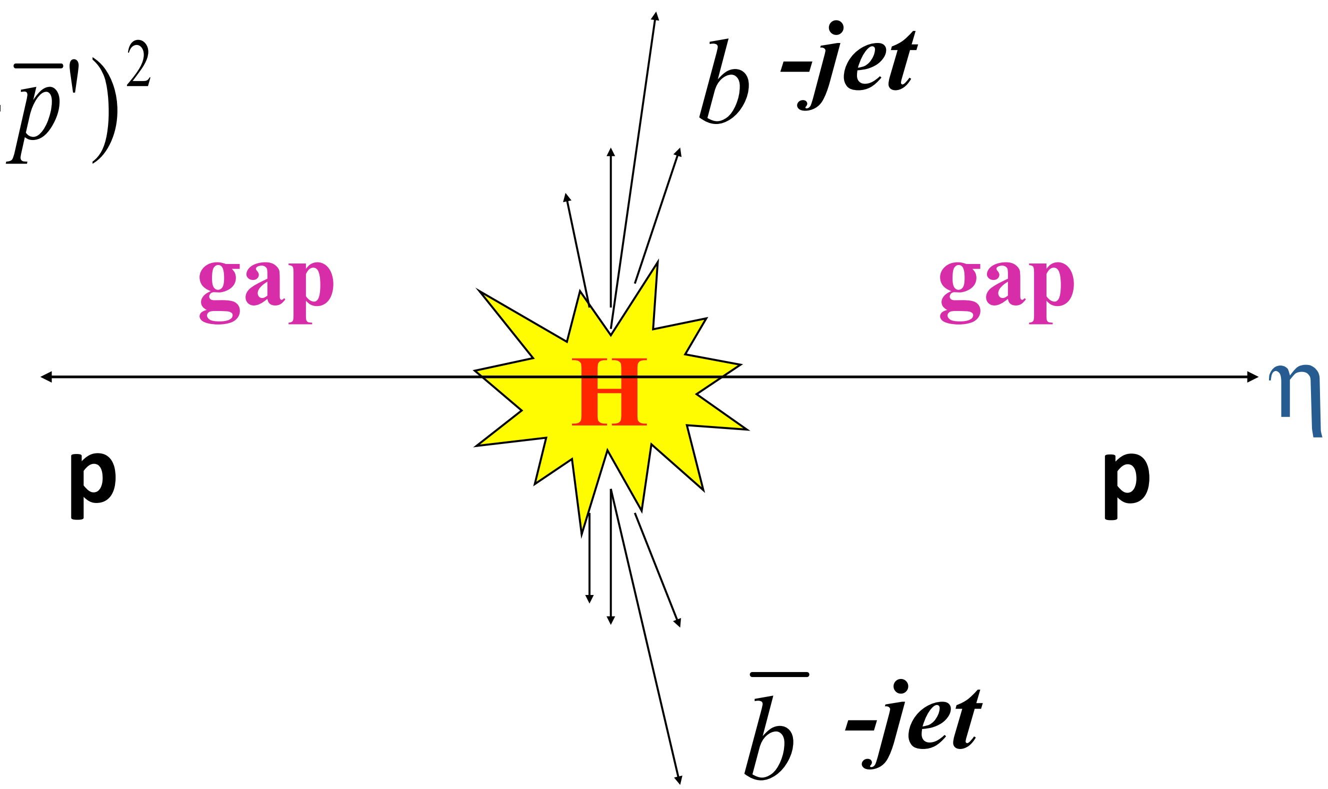
Central Exclusive Higgs Production

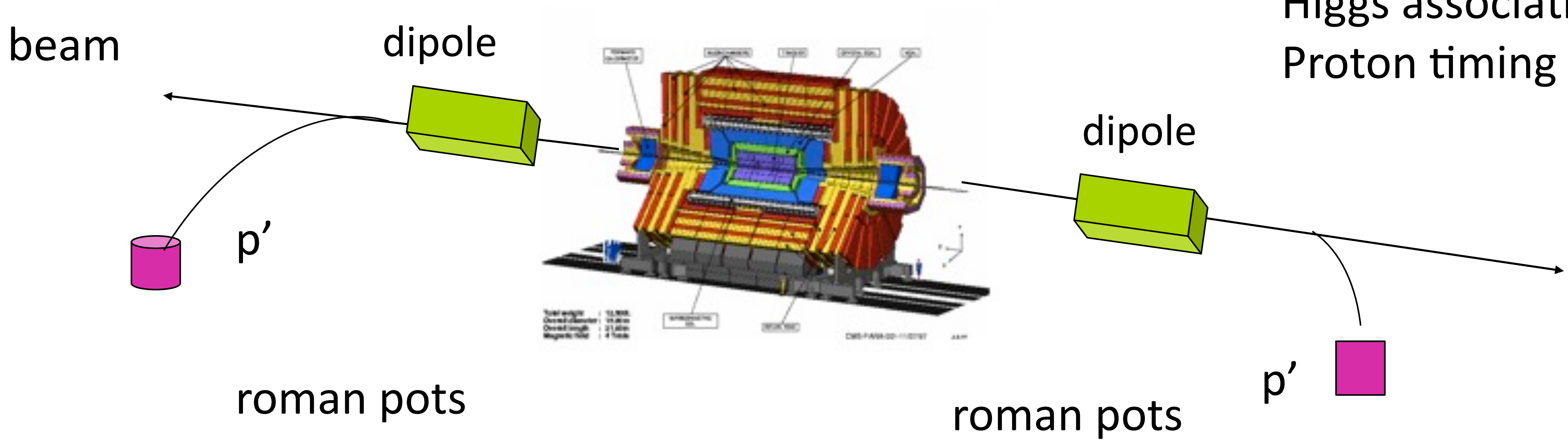
Central Exclusive Higgs production pp→p H p : >3 fb (SM)
~10-100 fb (MSSM)

$$M_H^2 = (p + \bar{p} - p' - \bar{p}')^2$$

$\Delta M = O(1.0 - 2.0)$ GeV

Background suppressed
By 0^+ selection rule



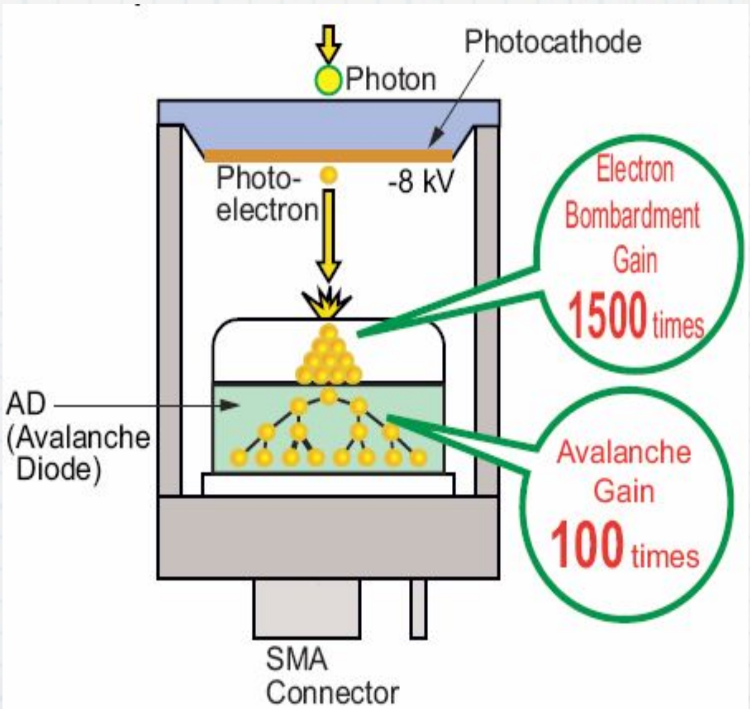


Higgs association from
Proton timing (~ 10 picosecond)

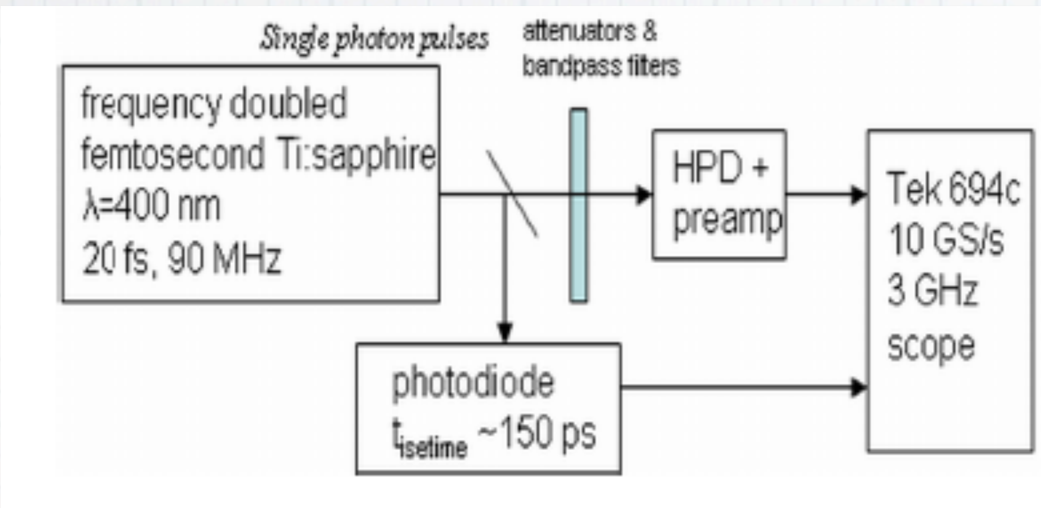
driver for faster timing @LHC is leading protons @L=10^{34}

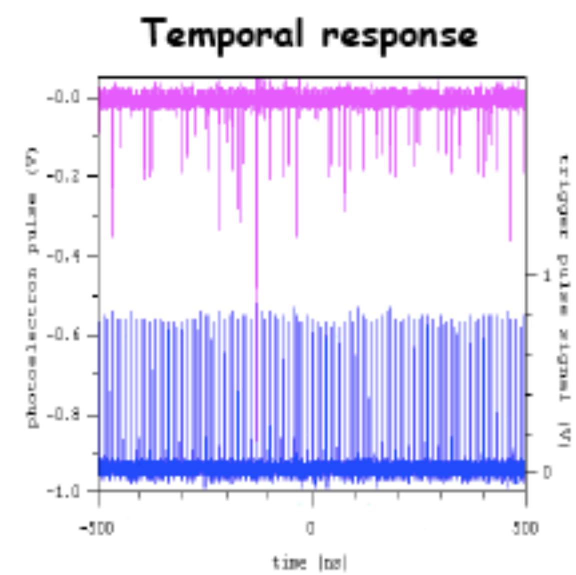
- encouraged by Brian Cox to look for new technologies that survive full Luminosity
- Hamamatsu (M. Suyama) provided a new device for evaluation. Lifetime tests show >250 Coulomb/cm^2 (cp. MCP, 20%loss @0.1 Coulomb)

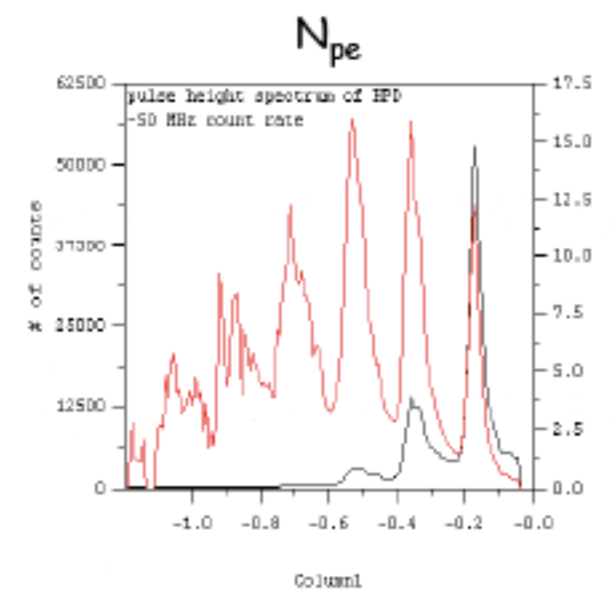
Communications industry->small area APDs w. G*BW>10^{11} Hz



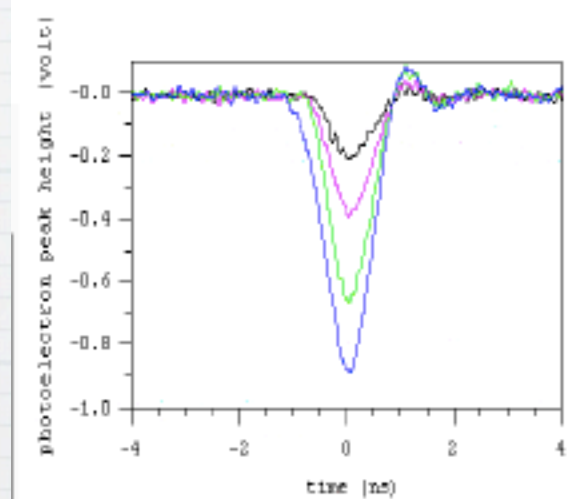
Applications in eg fluorescence spectroscopy
T.Tsang, S.White





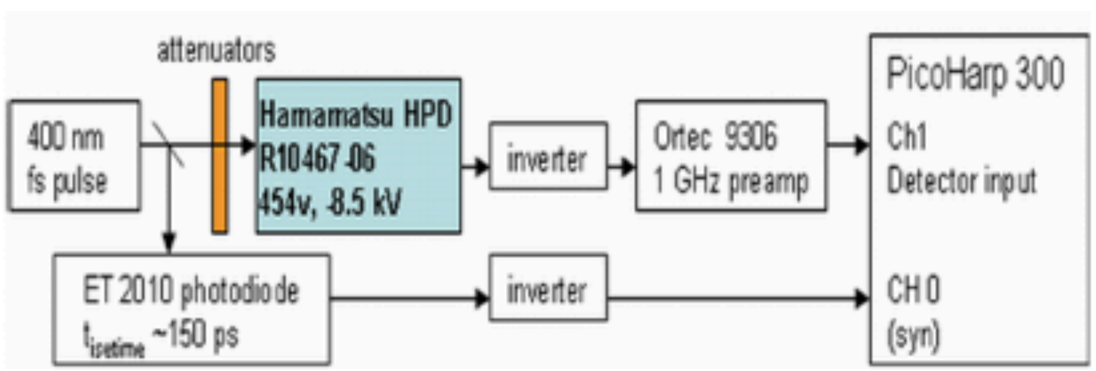


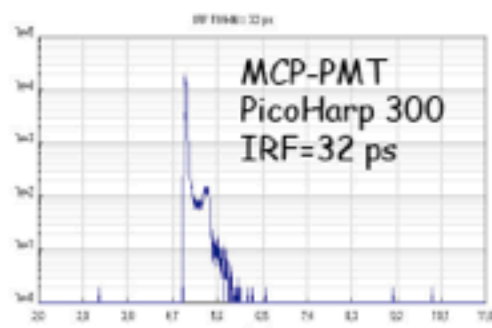
risetime=300 psec

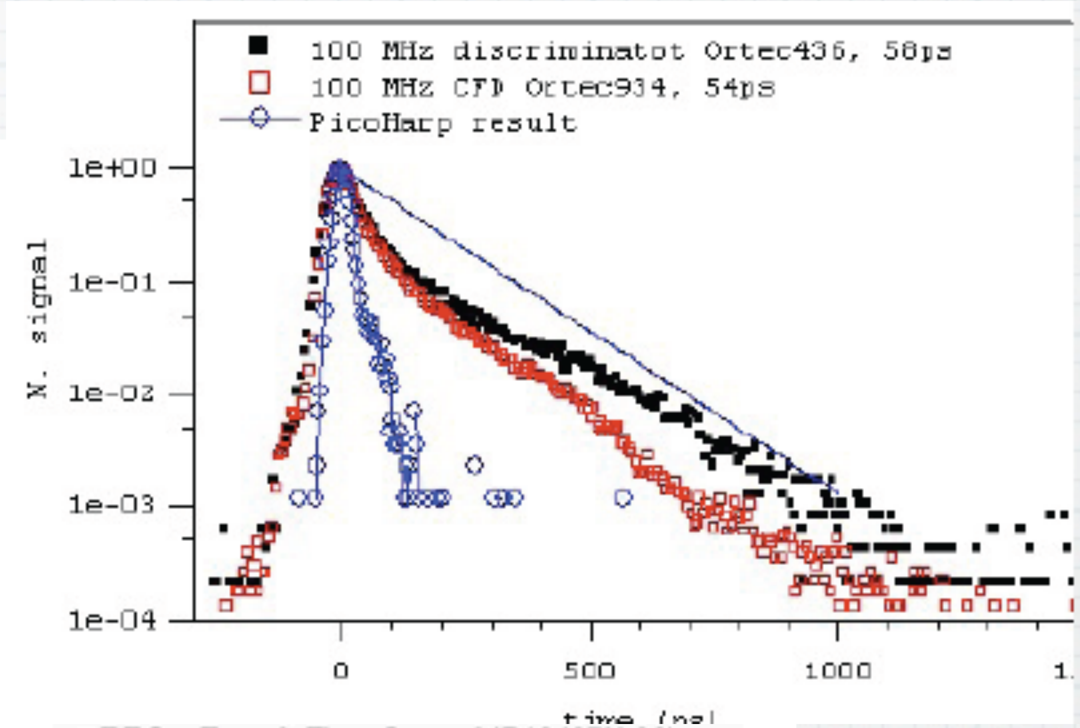


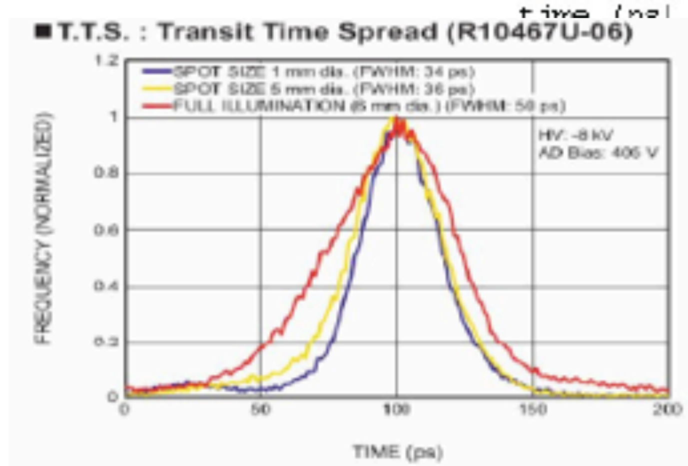
N_{pe}-	pulse height after preamp (Volt)	pulse height before preamp (mV)	normalized count rate
1	0.176	2.2	1
2	0.36	4.5	0.26
3	0.528	6.6	0.061
4	0.71	8.9	0.009
5			~0.0014
6			~0.0002

11 psec single photon response is not common. Below studies comparing LE, CFD, PicoHarp



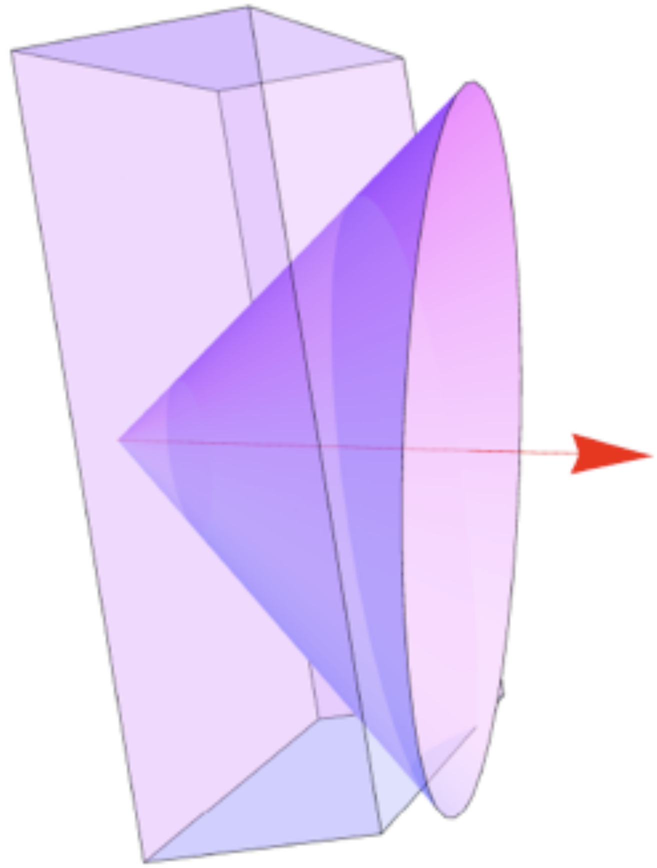




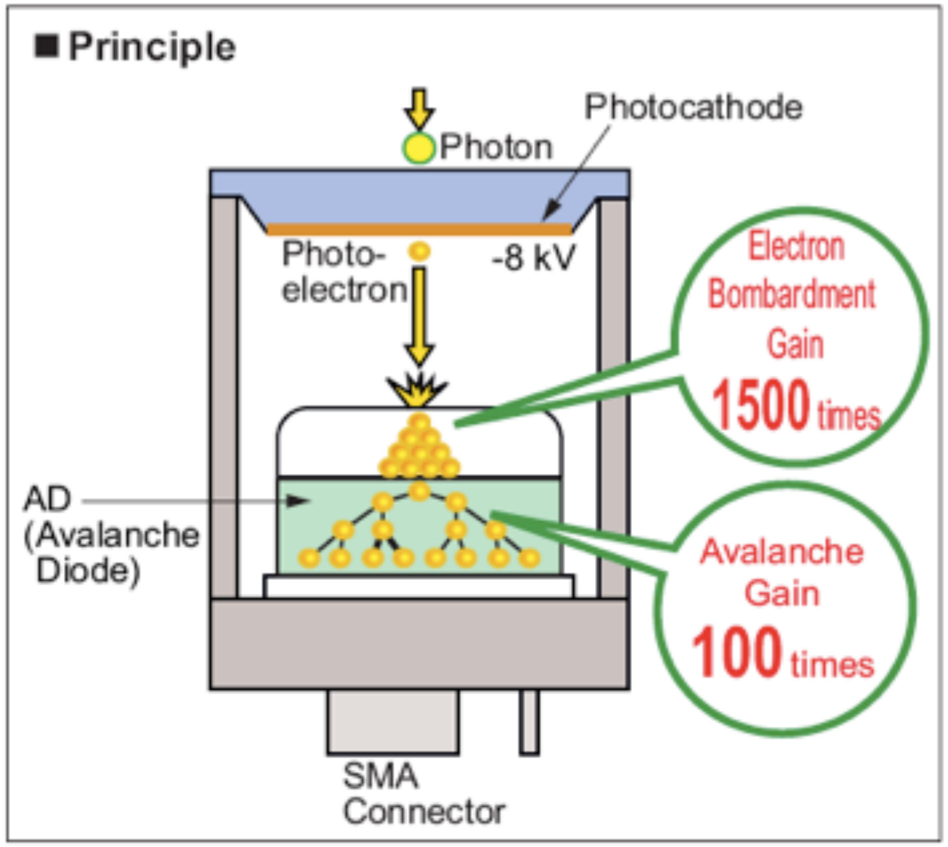


$$\sigma_{TOF} = \sqrt{\sigma^2_{HPD} + \sigma^2_{radiator} + \sigma^2_{electronics}}$$

$$\sigma_{HPD} = \frac{\sigma_{TTS}}{\sqrt{N_{pe^-}}} = \frac{11\,ps}{\sqrt{N_{pe^-}}}$$



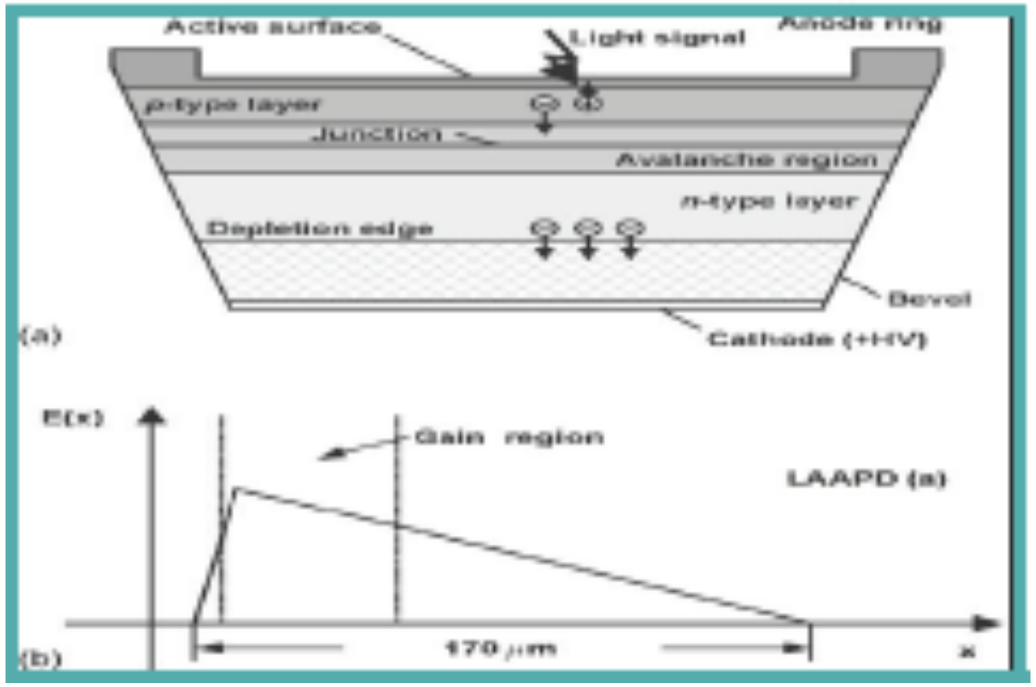
Cerenkov
or
APD
option

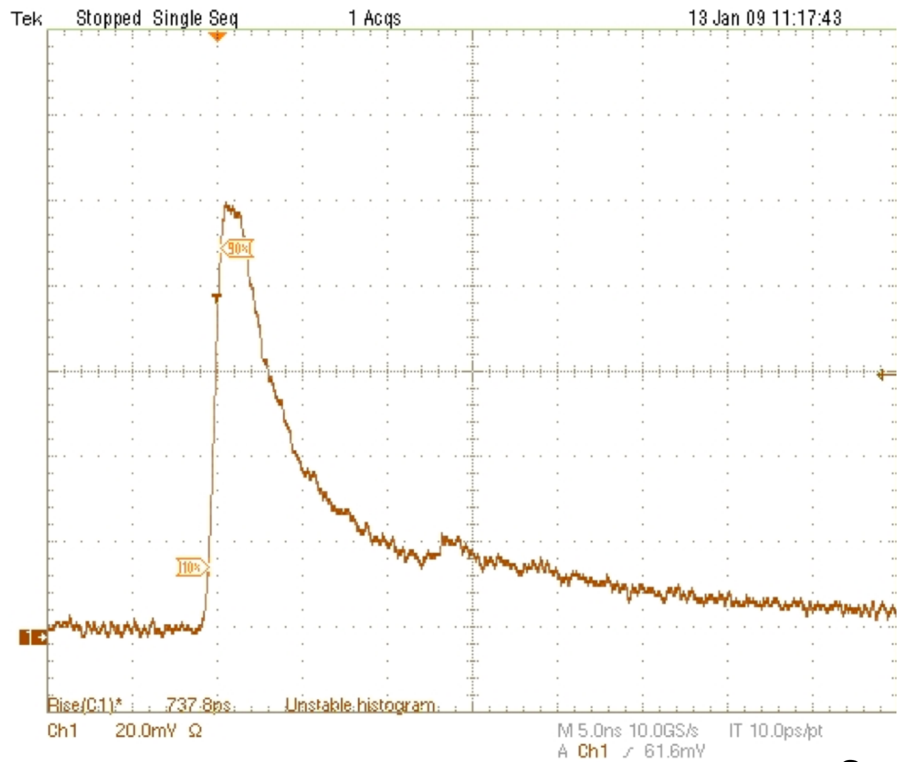


Cerenkov Radiation cone

Pre-production Hybrid photodetector

“A 10 picosecond time of flight detector using APD’s”, SNW et al.



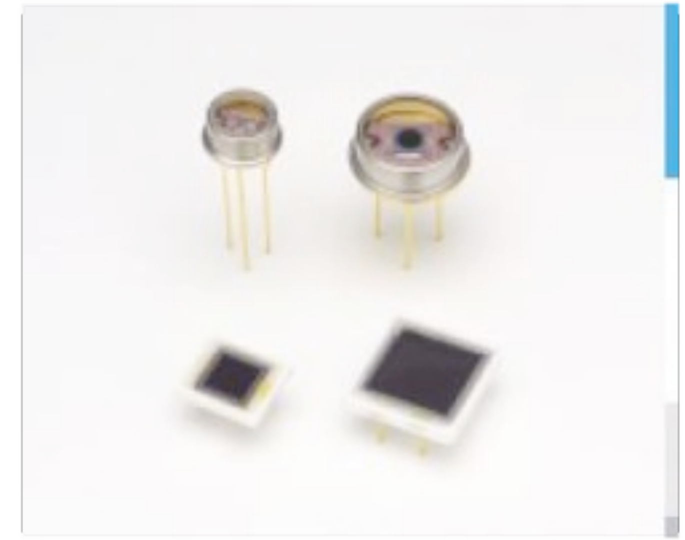


Deep diffused avalanche photodiode

650 picosecond risetime (β’s)

more robust APDs

* Hamamatsu 5*5 and 10*10 mm (from KOPIO)
* Perkin Elmer APDs (provided by ALICE)



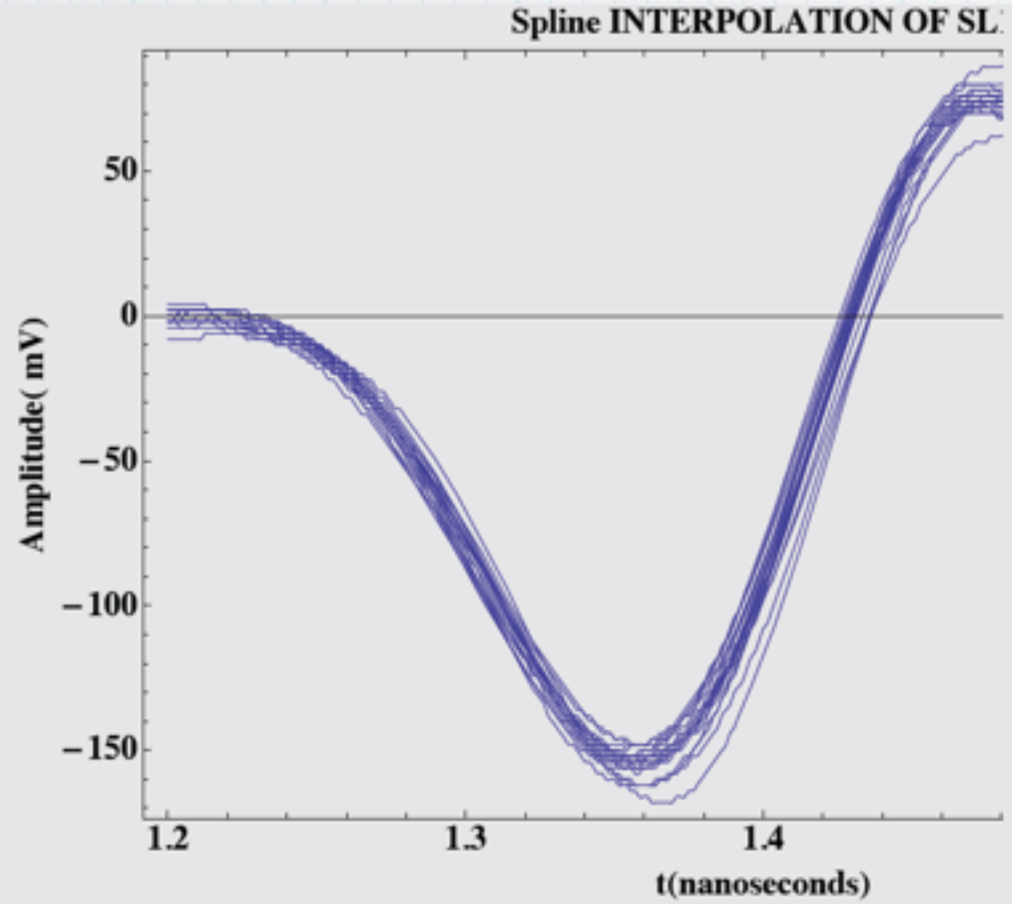
MCPs (Mickey Chiu has started to prepare these detectors, funded by PECAS)

The Plasma Panel Radiation Detector Development Project

...beating TVs into particle physics instrumentation since 2015

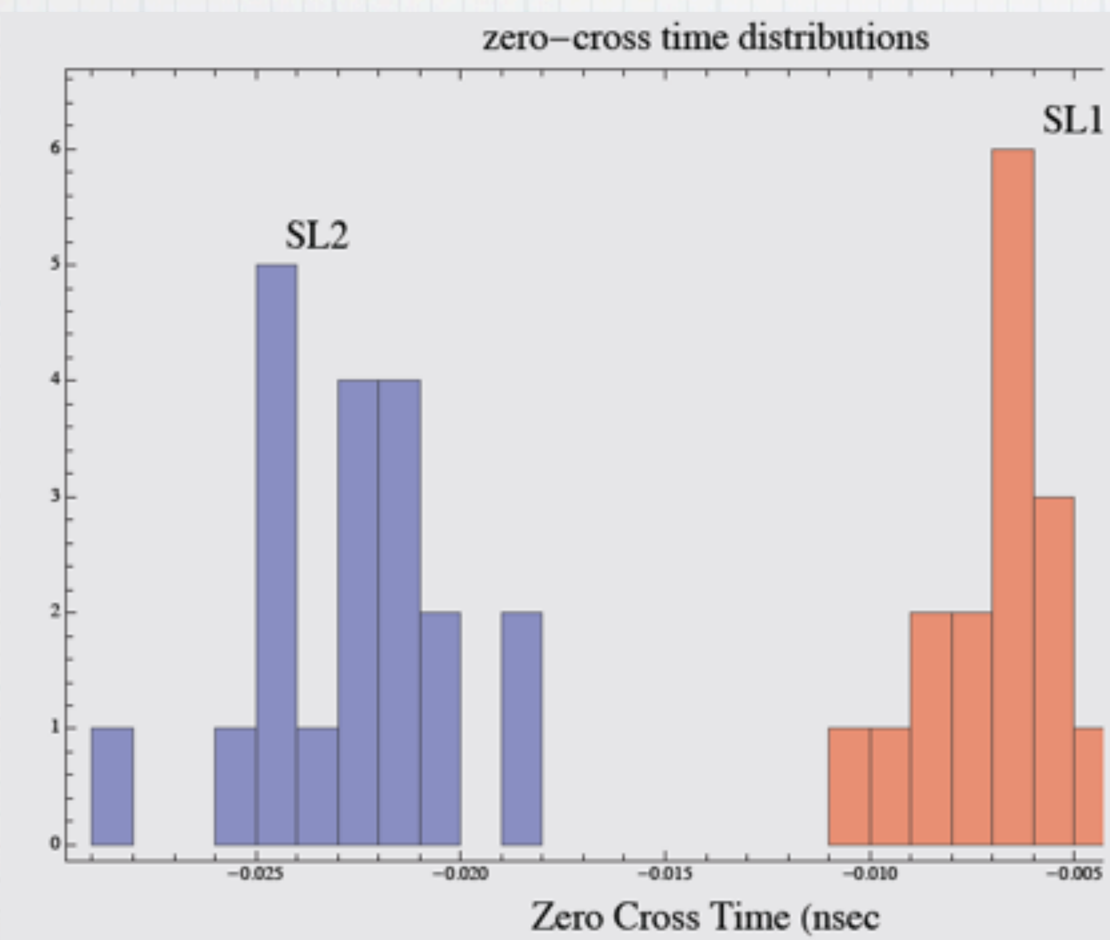
(not part of this proposal, possible interest in supplementary proposal)

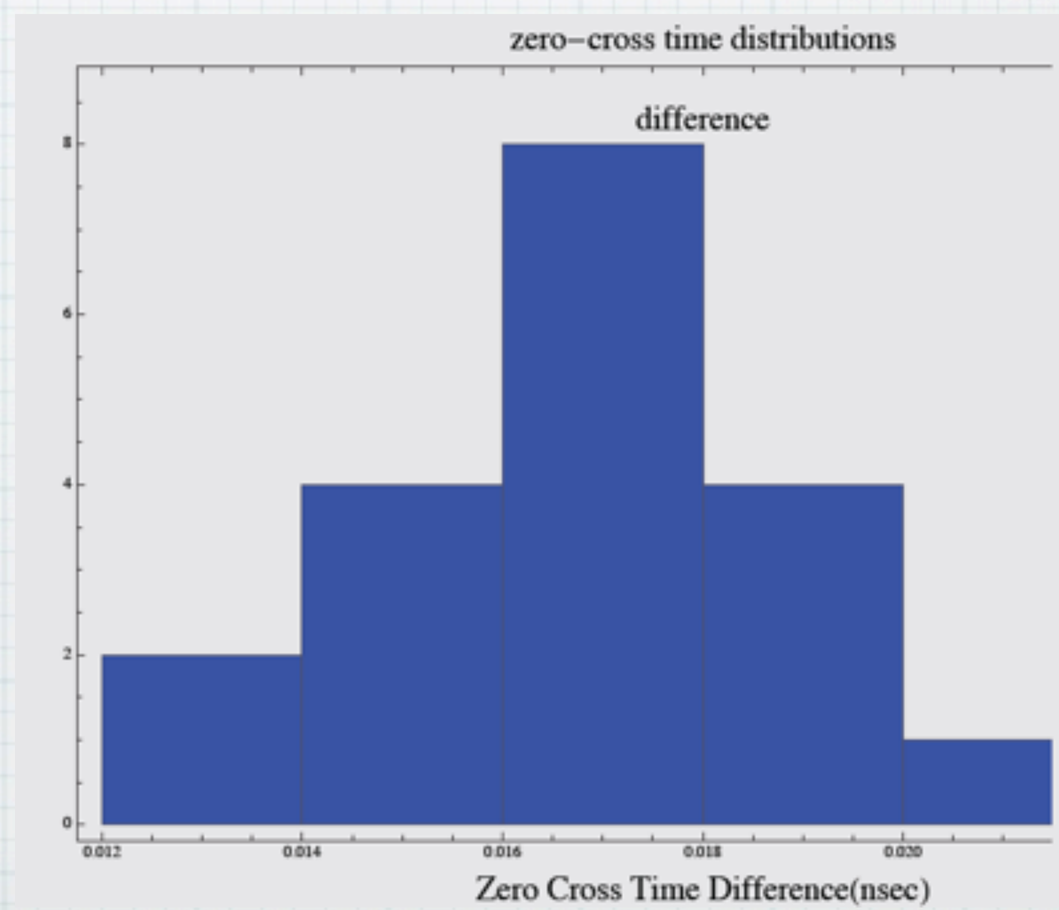
Initial study of "start time" resolution from ATF stripline

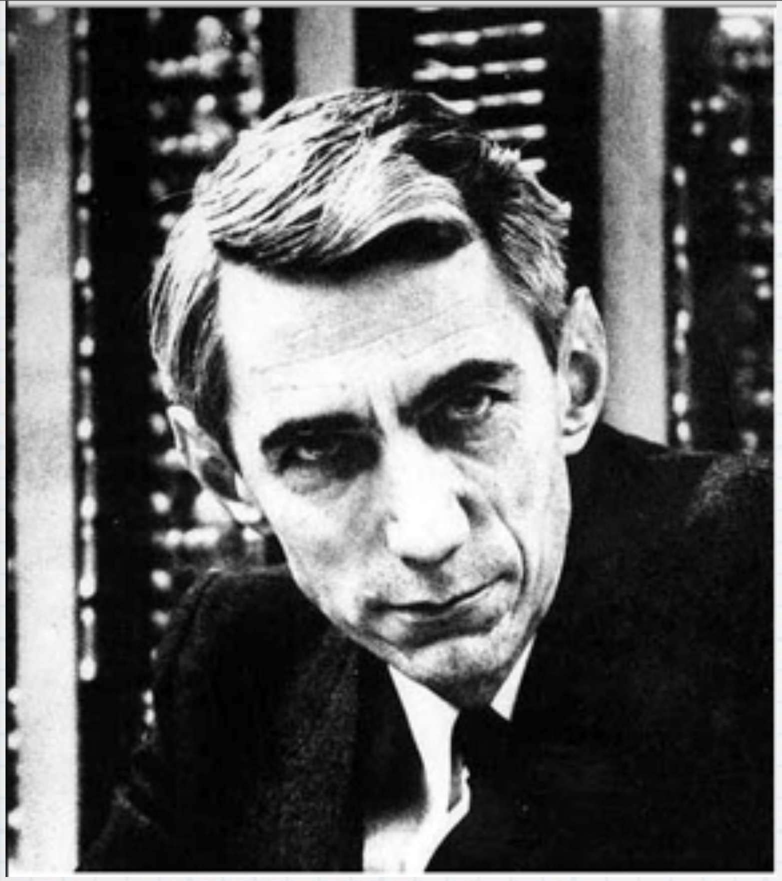


stripline waveforms w.
on-chip Sin[x]/x interpolation+spline

rms on time diff
between detectors <2.5 psec







Spinoff: experience at ATF has been very useful. Led to signal reconstruction algorithm for ATLAS ZDC. Now fastest detector in ATLAS (<100 psec)

- resulted in Shannon's 1940 PhD thesis at MIT, *An Algebra for Theoretical Genetics*[6]
- Victor Shestakov, at Moscow State University, had proposed a theory of electric switches based on Boolean logic a little bit earlier than Shannon, in 1935, but the first publication of Shestakov's result took place in 1941, after the publication of Shannon's thesis.
- The theorem is commonly called the **Nyquist sampling theorem**, and is also known as **Nyquist–Shannon–Kotelnikov**, **Whittaker–Shannon–Kotelnikov**, **Whittaker–Nyquist–Kotelnikov–Shannon**, **WKS**, etc., sampling theorem, as well as the **Cardinal Theorem of Interpolation Theory**. It is often referred to as simply ***the sampling theorem***.
- The theoretical rigor of Shannon's work completely replaced the *ad hoc* methods that had previously prevailed.
- Shannon and Turing met every day at teatime in the cafeteria.[8] Turing showed Shannon his seminal 1936 paper that defined what is now known as the "Universal Turing machine"[9][10] which impressed him, as many of its ideas were complementary to his own.
- He is also considered the co-inventor of the first wearable computer along with Edward O. Thorp.[16] The device was used to improve the odds when playing roulette.

In 1956 two Bell Labs scientists discovered the scientific formula for getting rich. One was the mathematician Claude Shannon, neurotic father of our digital age, whose genius is ranked with Einstein's. The other was John L. Kelly, Jr., a gun-toting Texas-born physicist. Together they applied the science of information theory—the basis of computers and the Internet—to the problem of making as much money as possible, as fast as possible. Shannon and MIT mathematician Edward O. Thorp took the "Kelly formula" to the roulette and blackjack tables of Las Vegas. It worked. They realized that there was even more money to be made in the stock market, specifically in the risky trading known as arbitrage. Thorp used the Kelly system with his phenomenally successful hedge fund Princeton-Newport Partners. Shannon became a successful investor, too, topping even Warren Buffett's rate of return and

no time to discuss Shannon's method for getting rich

will discuss Shannon's method for reconstructing digitized waveforms

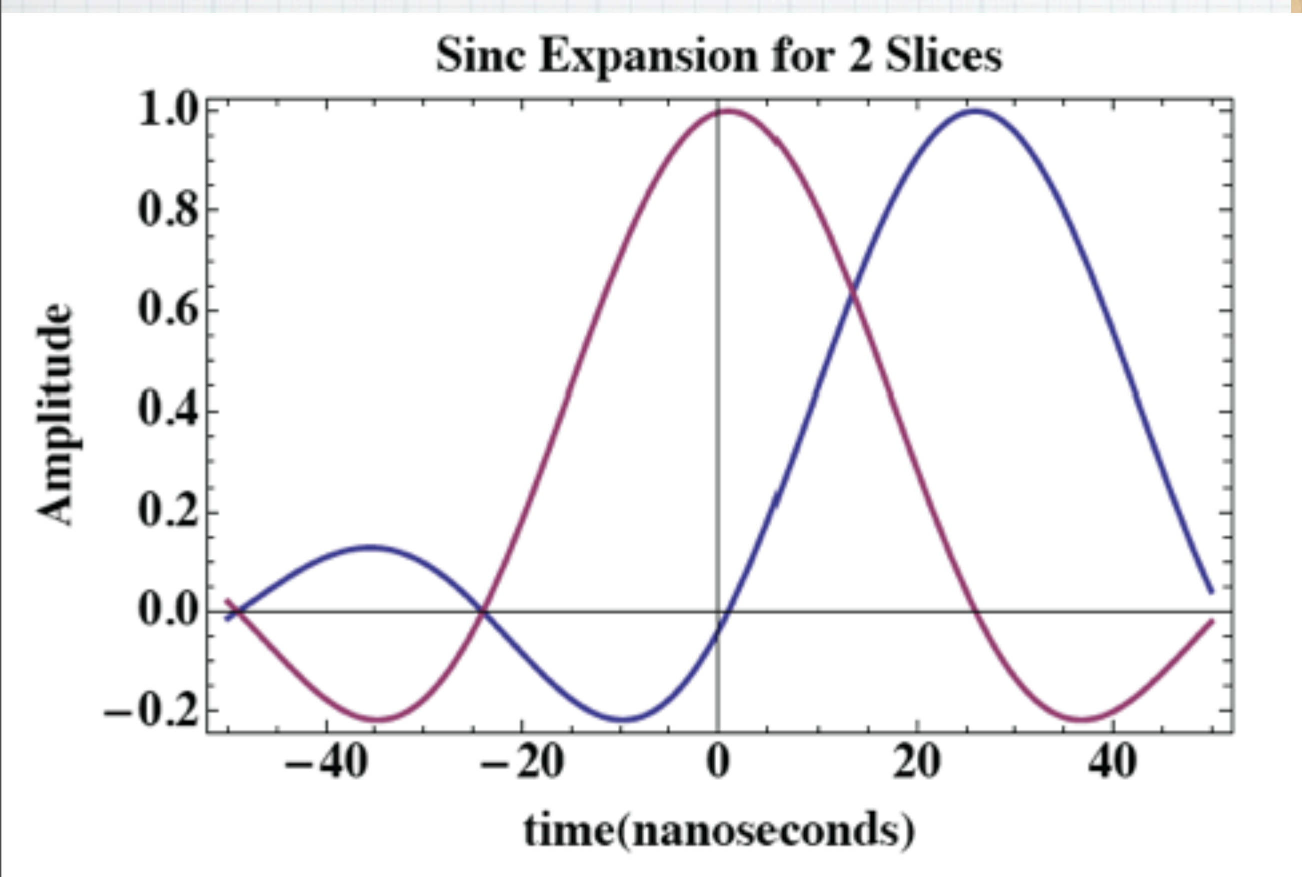
Reconstruction of ZDC Pre-Processor Data and its timing Calibration

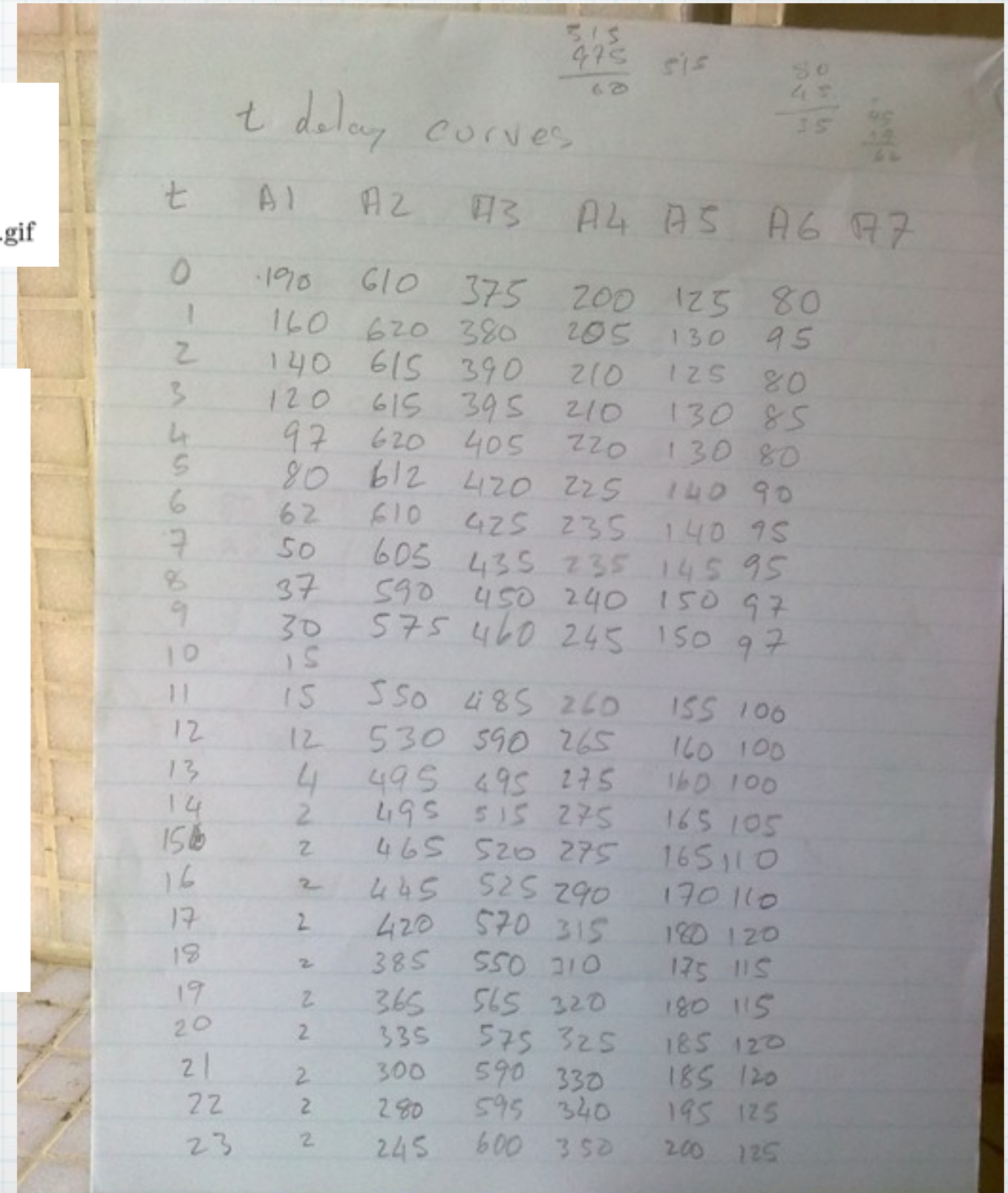
Soumya Mohapatra, Andrei Poblaguev and Sebastian White
Aug.8,2010

ATLAS data set used to develop ZDC reconstruction and do L1calo calibration (in Mathematica 7.0)

$$shannon[t] = \sum_{i=1}^{nslice} slice[i] \times Sinc[\pi \times (t - time(i))/25] \qquad (6)$$

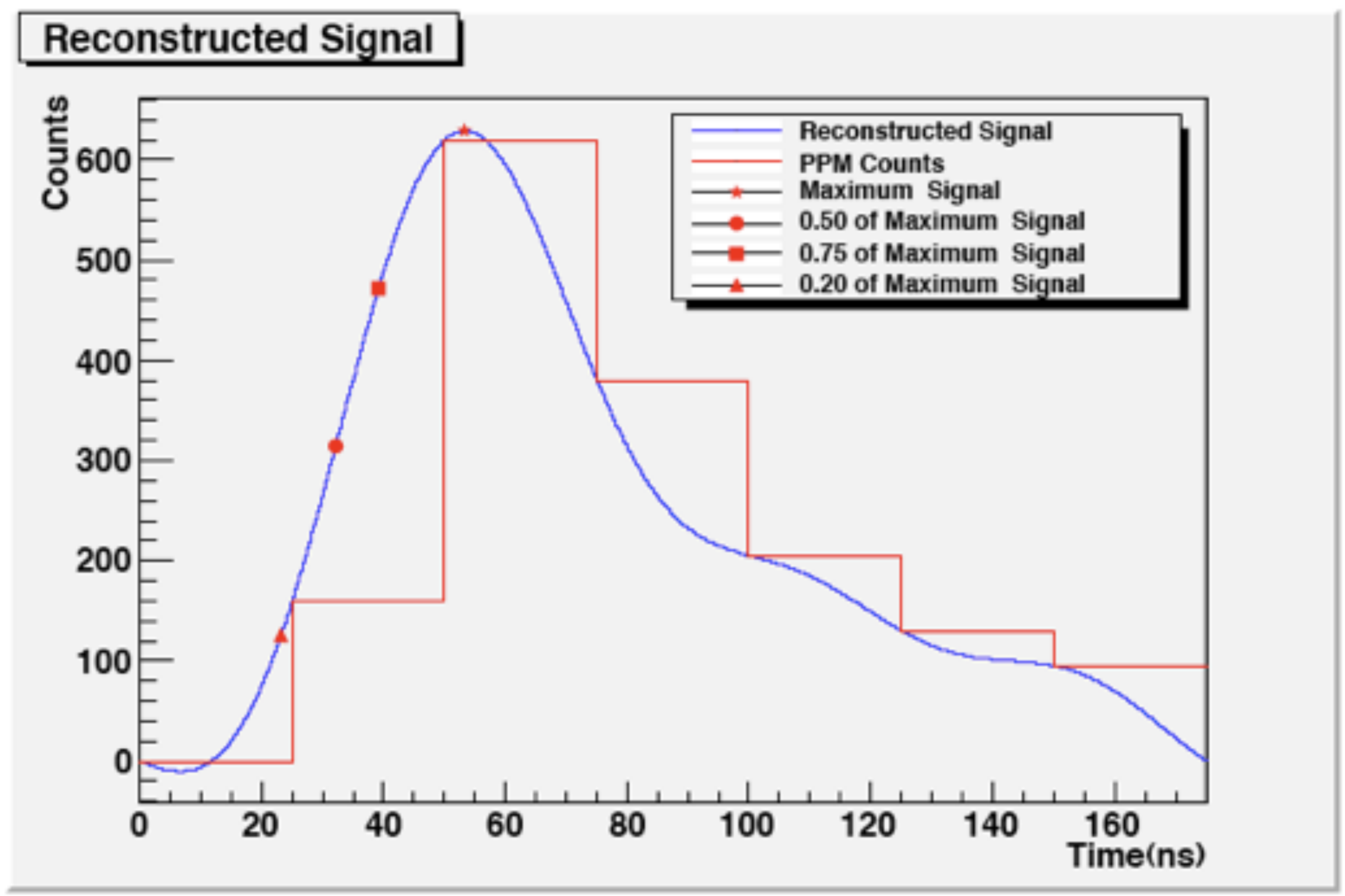
An animated gif can be found at:
http://www.phenix.bnl.gov/phenix/WWW/publish/swhite/ShannonFilm.gif

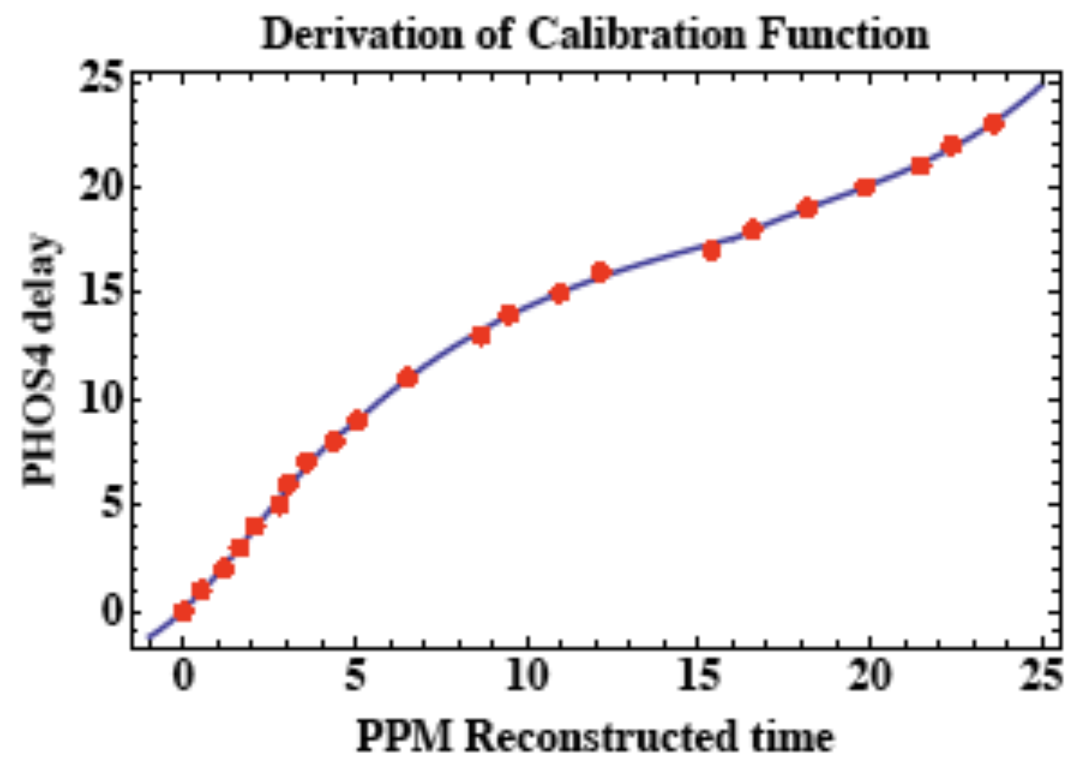




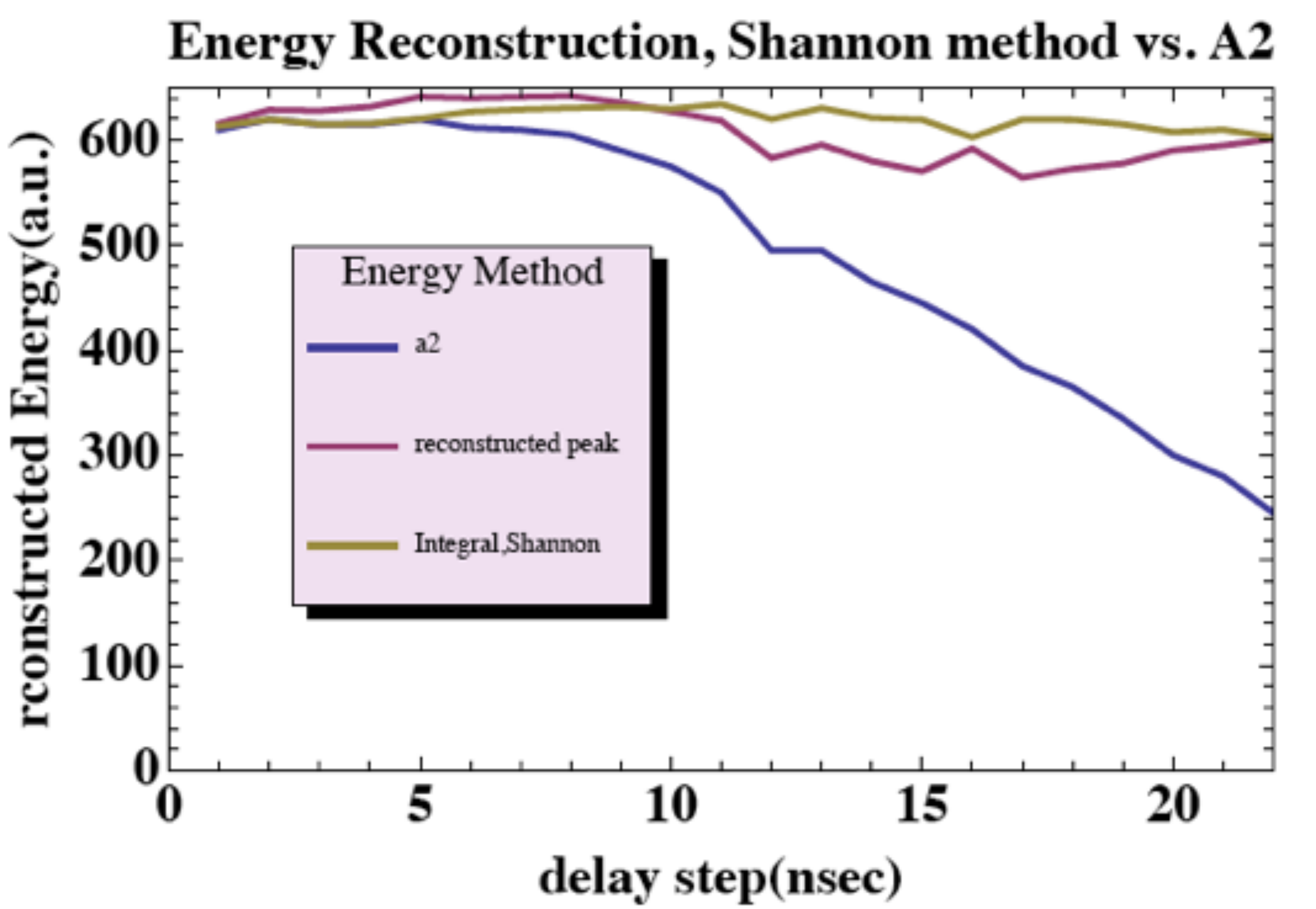
t delay curves

t	A1	A2	A3	A4	A5	A6	A7
0	·190	610	375	200	125	80	
1	160	620	380	205	130	95	
2	140	615	390	210	125	80	
3	120	615	395	210	130	85	
4	97	620	405	220	130	80	
5	80	612	420	225	140	90	
6	62	610	425	235	140	95	
7	50	605	435	235	145	95	
8	37	590	450	240	150	97	
9	30	575	460	245	150	97	
10	15						
11	15	550	485	260	155	100	
12	12	530	590	265	160	100	
13	4	495	495	275	160	100	
14	2	495	515	275	165	105	
15	2	465	520	275	165	110	
16	2	445	525	290	170	110	
17	2	420	570	315	180	120	
18	2	385	550	310	175	115	
19	2	365	565	320	180	115	
20	2	335	575	325	185	120	
21	2	300	590	330	185	120	
22	2	280	595	340	195	125	
23	2	245	600	350	200	125	

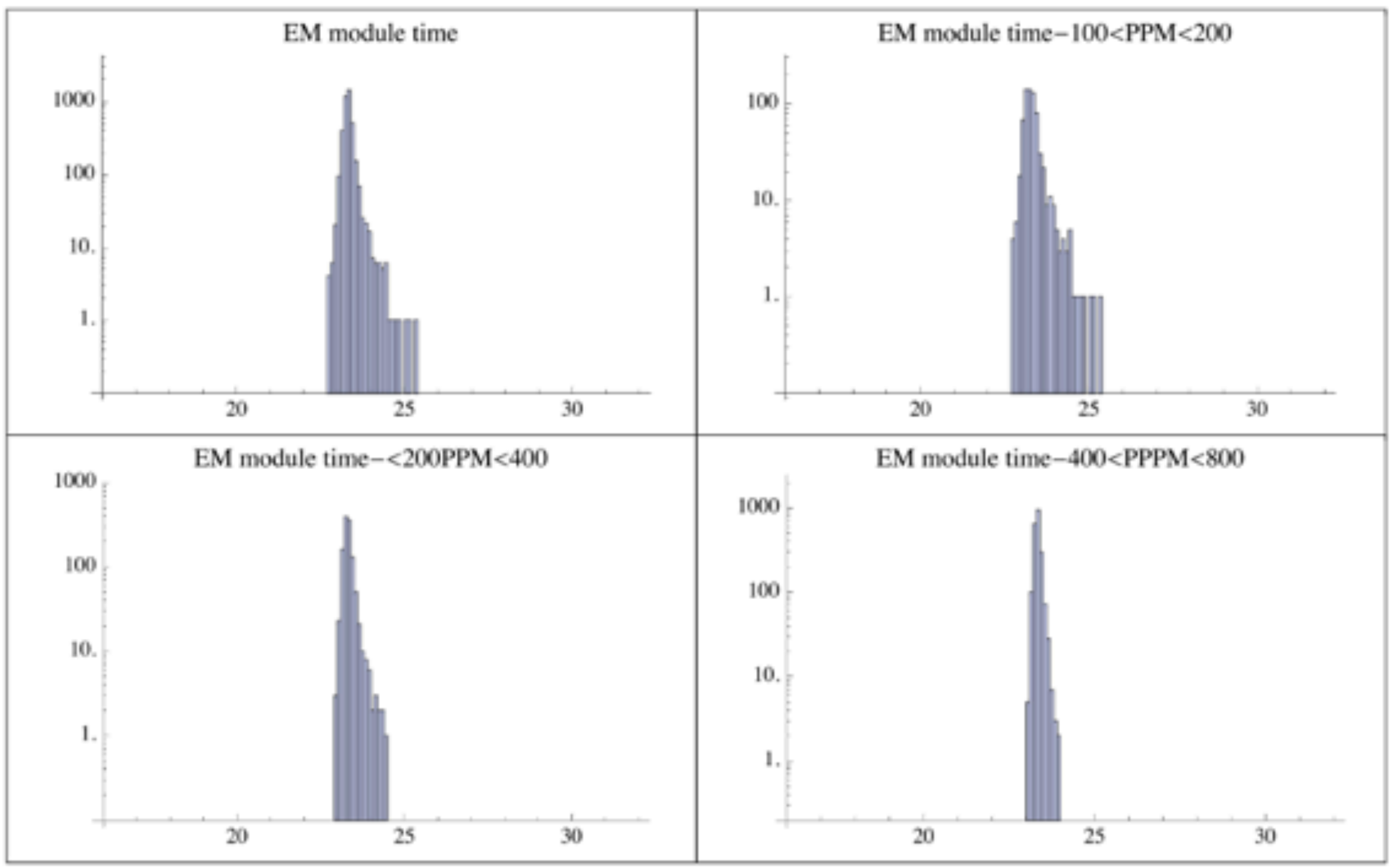




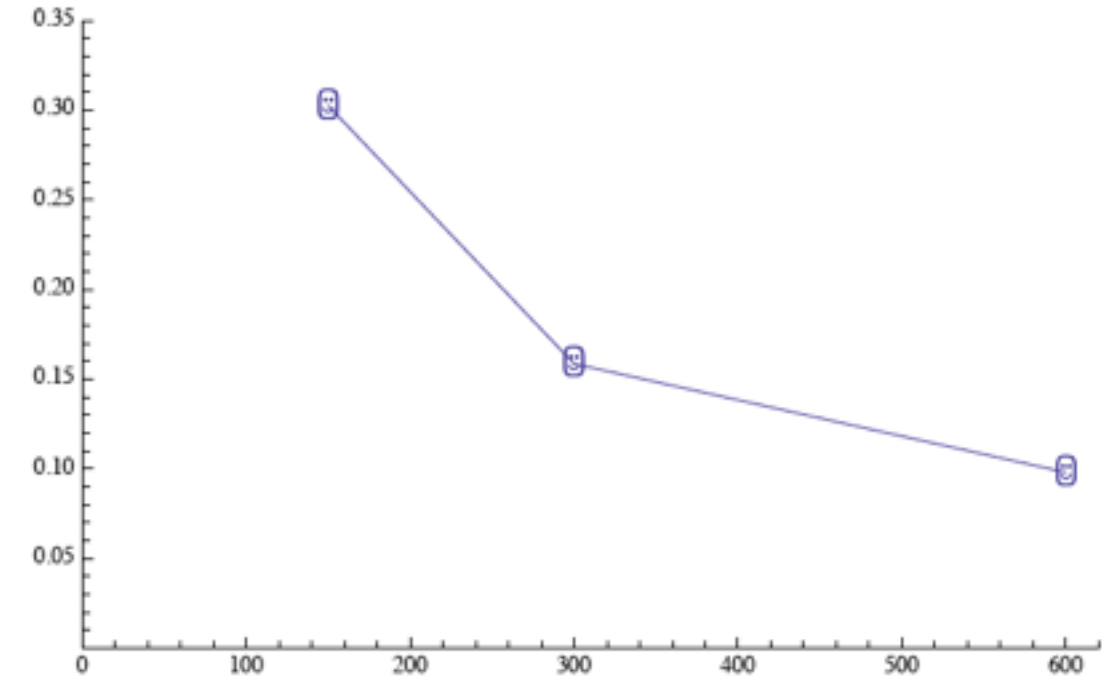
(d) Piecewise fit to the full range.



```
{7.0 for Mac OS X x86 (64-bit) (February 19, 2009), /Users/white, 15 786 240}

Timing[ATLASdata = Import["/afs/cern.ch/user/s/spagan/public/run160953.root"]] [[1]]

1.15994

nevents = Dimensions[ATLASdata][[1]]
{EMASignal, EMATime, EMAErrorFlag, HD0ASignal, HD0ATime, HD0AErrorFlag, HD1ASignal,
   HD1ATime, HD1AErrorFlag, HD2ASignal, HD2ATime, HD2AErrorFlag, EMCSignal,
   EMCTime, EMCErrorFlag, HD0CSignal, HD0CTime, HD0CErrorFlag, HD1CSignal, HD1CTime,
   HD1CErrorFlag, HD2CSignal, HD2CTime, HD2CErrorFlag} = Transpose[ATLASdata] ;

12 848

TEMA0 = Pick[EMATime, Thread[100 < EMASignal < 800]];
TEMA1 = Pick[EMATime, Thread[100 < EMASignal < 200]];
```



rms (nsec) of 3” H0 PMT vs. energy deposit



Application of commercial software to ATLAS data analysis

Dear Sebastian,

I have not yet contacted Tony as I also have been swamped with other tasks.

One potential issue of concern is that CERN ROOT is available under the Lesser General Public License (http://root.cern.ch/root/License.html). As I understand it (and I'll have this clarified by our legal department), we can not make use of any ROOT source code without exposing the Mathematica source code (which obviously is not an option). If true, this hurdle may be bigger than any technical problems we may face.

Ken

(I then held discussions with Brun and Rademaker at CERN, who were enthusiastic.)

Hello Sebastian,

I am sorry about the silence these days as I am still waiting on words from our legal department. I feel that it is best that I respond once I have any news on this front. In the mean time, I am taking the assumption that all will be legal, and have actually started to implement some items.

We are also very, very close to release here, and all our efforts are dedicated to it now. However, you can be assured that once Mathematica 8 is released, this will be a the first Mathematica 9 project I undertake.

Ken

Objectives

- we will evaluate performance of our timing detectors (all in hand)
- really a factory for new ideas in fast timing
- for photodetectors (HAPD and MCP) will follow path of Inami et al and Va'vra- timing resolution vs radiator thickness for proximity focused geometry
- depending on collaborator interest, will evaluate a radiator design specific to PHENIX upgrade

BACKUP

Addendum. Turn-key proposal to LBNE

Item	Value
RF operating frequency	2856 MHz
RF pulse flat-top duration	3 μs
Max. RF input power	10 MW
Max. accelerating gradient	100 MV/m
Max. beam energy at gun output	4.5 MeV
Bunch charge	0.1-1 nC
Repetition rate	10 Hz
RF operating frequency	2856 MHz
RF pulse flat-top duration	3 μs
Max. RF input power	15 MW
Max. accelerating gradient	20 MV/m
Max. energy gain per section	60 MeV
Repetition rate	10 Hz

The approximate breakdown of the total cost is as follows:

- Photoinjector gun system: $440,000
- Photocathode drive laser system: $481,000
- 100 MeV linear accelerator system: $628,000
- RF power system: $1,244,000
- Installation and commissioning support: $129,000